

**EXTENDING THE UTILITY OF MACHINE BASED HEIGHT SENSORS TO
SPATIALLY MONITOR COTTON GROWTH**

A Thesis

by

DAVID WILLIAM GEIGER

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

May 2004

Major Subject: Biological and Agricultural Engineering

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ABSTRACT

Extending the Utility of Machine Based Height Sensors
to Spatially Monitor Cotton Growth. (May 2004)

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The recommended procedures for implementing COTMAN; a cotton management expert system; suggest frequent crop scouting at numerous locations for each field. Machine based height sensors coupled with the ability to spatially record height values make it possible to locate regions of a field that are height representative of the entire field. A machine based height measurement system called HMAP was used to assess plant height in various fields in the 2003 growing season while the same fields were monitored with COTMAN. The plant height data was used to determine an optimal COTMAN sampling scheme for each field consisting of significantly fewer sampling locations than recommended by COTMAN. It was possible to ascertain equivalent information from COTMAN using two sites selected from height data in place of six sites selected per COTMAN recommendations. The HMAP system was extended to monitor rate of growth in real time in addition to plant height by comparing historical plant height data recorded on previous field passes to current height values. The rate of growth capable HMAP system will make it possible to track cotton growth and development with an automated system.

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INTRODUCTION

BACKGROUND

In the lean farm economy that is reality today, profitability is dependent on sound management decisions. Agronomists at the University of Arkansas developed an expert management software package called COTMAN to aid cotton producers in making important management decisions. COTMAN uses a combination of field observations, plant mapping, and meteorological data to track the physiological development of cotton throughout the growing season. COTMAN has become an important management tool for both researchers and cotton producers. While it is a powerful and proven tool, there are still opportunities to enhance the value it provides.

First, COTMAN is a field scale management system. Crop scouting is conducted at various locations throughout the field in order to obtain a cross section of samples that characterize the general or average condition of the field. Many management factors such as requirements for irrigation, insect control, plant growth regulators (PGRs) such as mepiquat chloride (PIX®), and defoliants can vary significantly across the field. Management zones are often restricted to the farm or field level due to a lack of data which can be used to identify smaller management zones. Second, selection of sampling locations by crop scouts is a highly subjective process that does not always result in sampling locations that realistically characterize the field. While crop scouts may attempt to select samples representative of the field, it is difficult for even the most

This thesis follows the style and format of *Applied Engineering in Agriculture*.

experienced scouts to select samples that realistically represent the population of the field. Third, COTMAN requires frequent in-field data collection which is time consuming and labor intensive. Over the course of the season, such investments become substantial. Reducing the manual inputs required for COTMAN provides an opportunity to lower the costs associated with implementing COTMAN while maintaining the management value. Precision agriculture data sources such as plant height maps, yield maps, and aerial imagery could provide a means to more accurately assess field conditions by selecting better sampling locations and decrease the costs associated with implementation by minimizing field sampling requirements.

Expert management systems such as COTMAN and crop modeling systems such as GOSSYM attempt to monitor and predict, respectively, the effects of management decisions on cotton development. While both systems track a variety of parameters associated with the physiological development of cotton, they are ultimately tracking/modeling aspects of crop growth rate. A variety of measures of crop growth rate have been proposed. COTMAN tracks nodes above first square (NAFS) and nodes above white flower (NAWF) relative to a target development curve based on accumulated heat units and historical meteorological data. Plant height is another parameter that can be used to track crop growth rate. Plant height over time or rate of growth directly creates a measure of crop growth rate with respect to plant height. Researchers have developed empirical relationships between cotton plant height and plant biomass. By correlating plant height to plant biomass, it is possible to generate another measure of crop growth rate with respect to biomass. A Texas A&M University (TAMU) developed machine

based spatial height mapping system known as HMAP has the ability to spatially record plant height across a field and adjust plant growth regulator application rates in real time based on empirical relationships between plant height and biomass developed by agronomists. Spatial height data or biomass data recorded with the HMAP system can be used to monitor crop growth rate with respect to plant height and biomass. By comparing current HMAP height data with historical height data recorded on previous field passes it becomes possible to directly monitor crop growth rate. While plant height data from different dates can be collected and post-processed using a variety of methods, the HMAP system provides a unique opportunity to collect and process data in real time.

Agricultural equipment performing routine field operations provides a valuable opportunity to observe crop. Precision farming technologies have made data collection operations such as yield mapping during harvest commonplace; however, data is not collected during the majority of non-harvest operations. A lack of commercially available data collection equipment for non-harvest operations and a lack of decision support systems to translate field observations into management decisions both contribute to the limited utility of collecting such data. In cotton, frequent applications of chemicals such as insecticides and plant growth regulators provide an opportunity for data collection during routine spraying operations throughout the season. The HMAP system integrated with MEPRT, a software application used to determine plant growth regulator application rates and timing, uses plant height data along with other pre-defined parameters such as row spacing and plant density to spatially vary plant growth regulator application rates in real time. Real time variable rate application (VRA) of

plant growth regulator provides more effective utilization of chemicals than traditional constant rate methods by spatially targeting plants with the greatest need for PGRs, however, research has shown that total chemical use efficiency and lint yield are virtually unaltered. In the current HMAP system, tall plants always receive the highest application rate without regard for the effects of previous applications. Plant growth regulator usage could potentially be reduced by considering rate of growth in addition to plant height when calculating application rates. Rather than targeting all tall plants with the highest application rate, only tall plants that are vigorously growing would be targeted with the highest rate thereby reducing overall PGR usage by not applying excess PGR on plants where the rate of vegetative growth was already reduced by previous PGR applications or other factors that can limit growth.

RATIONALE AND SIGNIFICANCE

COTMAN is a software based expert system that interprets in-season data to detect plant stress, monitor plant development, and aid in scheduling end-of-season activities such as insecticide termination and harvest initiation (Bourland et al., 1994). Growth curves generated by COTMAN can be used to quickly identify potential problems (Klein et al., 1994). Oosterhuis et al. (1996) determined through research in Arkansas that the cost savings from using COTMAN for timing insecticide termination alone would result in savings between \$14.13/hectare and \$63.70/hectare (\$5.72/acre and \$25.78/acre) depending on region. The benefits of COTMAN are clear; however, intensive manual data collection has hindered acceptance by producers, and many that do use it cut

corners by not collecting the data in the quantity or frequency recommended by COTMAN. Cochran et al. (1999) addressed long standing concerns regarding appropriate sampling schemes for COTMAN. They determined that increasing the number of sampling sites over COTMAN recommendations has significantly less effect than increasing the number of plants sampled at each site. The study determined optimal sampling schemes for various parameters; a comparison of COTMAN recommendations and the optimized scheme is summarized in Table 1.

Table 1: Comparison of COTMAN Sampling Schemes

	COTMAN	Optimized
Plant Height	4-8 sites	5-11 sites
	2 measures per site	2-4 measures per site
Squaring Nodes	4-8 sites	3-10 sites
	10 plants per site	7-14 plants per site
Square Relation	4-8 sites	2-7 sites
	10 plants per site	11-27 plants
NAWF	4-8 sites	3-8 sites
	10 plants per site	7-23 plants per site

Stewart et al. (2000) concluded through a study in North Carolina that the time inputs of COTMAN were excessive for the type of information received. They pointed out that in North Carolina the average cotton field size is 5.7 hectares (14.2 acres) which requires four sampling sites per COTMAN recommendations.

More careful consideration of sampling locations could offer added value to COTMAN by more efficiently and accurately assessing field conditions. Various studies have been conducted to estimate the costs associated with implementing COTMAN when using COTMAN sampling recommendations. Robertson et al. (1997) determined that the direct cost of sampling for once weekly COTMAN scouting ranged

from \$3.14/hectare to \$4.32/hectare (\$1.27/acre to \$1.75/acre) and \$8.62/hectare (\$3.49/acre) for twice weekly monitoring. Teague et al. (2000) determined that time requirement for each 4.0 hectares (10 acres) of field size of 12 minutes per sampling. Assuming the same labor parameters as the Robertson et al. study (10 weeks, \$7.00/hour), this roughly correlates to \$3.46/hectare (\$1.40/acre) for once weekly and \$6.92/hectare (\$2.80/acre) for twice weekly scouting neglecting travel and management costs assumed in the Robertson et al. study. The results of these studies are comparable. While the benefits of COTMAN undoubtedly outweigh the costs associated with implementation, the costs are significant and could be reduced if field scouting requirements were reduced. The HMAP system developed by Searcy and Beck (2000) provides an opportunity to reduce the number of sampling locations needed to characterize the general condition of a field by spatially identifying locations in the field that realistically represent the average conditions present. COTMAN generates development curves to track cotton development and crop growth rate relative to an ideal curve. Further enhancements of the HMAP system such as rate of growth determination may also provide opportunities to reduce the frequency of COTMAN field sampling through automated monitoring of crop development. Similar developmental information could be ascertained from rate of growth data by comparing actual rate of growth to an ideal rate of growth model. Kennedy and Hutchinson (2001) concluded that lint yield was correlated to early season crop growth rate, in particular, height. The HMAP system could monitor such parameters without crop scouting while providing the same look-ahead knowledge to the producer. An extended HMAP system with the ability to

monitor and record rate of growth in addition to plant height could also enhance many management decisions outside of COTMAN by providing an inexpensive means through which crop growth rate could be evaluated.

Lint yield and quality are maximized when the number of open bolls present at harvest is maximized. This is achieved when an optimum balance between vegetative and reproductive growth is maintained (Kerby et al., 1990; Kerby et al., 1997). Plant growth regulators such as PIX® are used to slow vegetative growth (Fernandez et al., 1992; Kerby et al., 1982; Reddy et al., 1990; Reddy et al., 1992; Stuart et al., 1984; York, 1983; Zummo et al., 1984) and thereby maintain such a balance. A study by Cothren (1979) indicated that PIX® usage could increase the number of harvestable bolls. Bourland and Watson (1990) and Kerby et al. (1986) showed in separate studies that mepiquat chloride causes a redistribution of bolls away from the main stem, possibly to more accessible harvesting locations while the total number of bolls remains constant. The effects of PIX® on yield have been inconsistent (Kerby et al., 1986); however, other benefits such as improved water and carbon efficiency have been well documented (Fernandez et al., 1992).

Weir et al. (1991) concluded that lint yield can be improved through the use of constant rate PIX® application throughout the growing season. Variable rate plant growth regulator application offers an approach that addresses field variability by targeting taller plants with more plant growth regulator than shorter plants. Research efforts by Munier et al. (1994) with operator controlled VRA based on visual assessment of plant height and by Beck (2001) with real time variable rate application based on

machine measured plant heights have also produced mixed results. In some trials yield was increased by variable rate application; however, yield affects between variable rate application and constant rate application were generally inconclusive. Thurman and Heiniger (1999) concluded that constant rate PIX® application actually increases spatial variability with respect to plant height and height to node ratio. This phenomenon suggests that management practices which directly address spatial variability such as variable rate PIX® application could be used to reduce spatial variability while still realizing the benefits of cotton PGRs. The Munier et al. (1994) VRA system relied on operator interpretation of chains hanging from the sprayer indicating tall, medium, and short regions across the field. The operator varied the application rate by selecting one of three discreet pre-determined application rates corresponding to each height category. The Beck (2001) system utilized the HMAP system's ability to measure plant height in real time during the spraying operation and continuously vary PIX® application rates based on plant biomass according to the MEPRT relationships described by Landivar (1998). While the real time HMAP system provides a more concrete assessment of plant height than the discreet interval system, neither system fully takes into account the effects of previous plant growth regulator applications on a site specific basis; tall plants and tall vigorously growing plants are treated alike. It is theorized that if rate of growth is considered along with plant height in variable rate application of plant growth regulators, both yield and chemical usage can be significantly improved over constant rate application. The HMAP system provides a platform and means to make such acquisitions possible.

OBJECTIVES

Hypothesis: Machine based height sensors can generate spatial maps of plant height that can be used to directly monitor the growth and development of cotton and to aid in cotton management when used in conjunction with COTMAN, a popular cotton management expert system.

The following objectives will be investigated in order to validate the fore mentioned hypothesis:

1. Utilize machine based height measurements and other precision agriculture data sources to optimize in-field plant sampling schemes for COTMAN.
2. Develop and validate software and methodologies to allow a machine based height measurement system to determine cotton rate of growth in real time.

PRECISION AGRICULTURE: AN INPUT FOR COTMAN

The subsections of this article are presented in two parts: the first three subsections are presented and formatted as a journal article manuscript; the final subsection titled “Additional Details” contains additional information not included in the journal manuscript.

INTRODUCTION

OVERVIEW

The determination of field sampling locations for COTMAN software is a highly subjective process. COTMAN provides guidelines for field sampling with respect to methods and numbers. Many producers do not adhere to the guidelines because of frequent and intensive manual sampling requirements. The utility of COTMAN can be enhanced by selecting management schemes that address spatial variability present in the field and by selecting field sampling schemes that minimize manual sampling requirements. Research was conducted at Texas A&M University (TAMU) in 2003 to explore the concept of using machine based height sensors and other precision agriculture technologies to aid in selecting optimal management and sampling schemes for COTMAN. Test sites which consisted of production irrigated and dryland fields in the coastal plains and Brazos Valley regions of Texas were monitored throughout the growing season by COTMAN and a TAMU developed spatial plant height mapping system called HMAP. Regions of each field that continually exhibited height

characteristics consistent with the field average were identified from the plant height data. Two sampling locations selected from consistently average height regions within a field were able to generate equivalent COTMAN outputs to those generated with two to three times as many sampling locations per COTMAN recommendations from the same field for all sites considered in this study, irrespective of field size.

BACKGROUND

COTMAN is a software based decision support system for cotton that uses manually collected field data to provide management related feedback to producers. The utility of COTMAN can be maximized by using the least possible labor input to still obtain useful and accurate output information. Maximizing the input to output ratio for COTMAN can be accomplished by selecting optimal management and sampling schemes for a particular field.

The optimal management scheme for a particular site depends on many factors relating to field conditions and the producer. In a field scale management scheme, the entire field is managed as a single unit and the desired outputs from COTMAN are management recommendations that reflect the general condition of the field. In a sub-field or site specific management scheme, each field is divided into smaller management zones that share similar characteristics and the desired outputs of COTMAN become management recommendations for each zone.

Producers must have knowledge of the amount of developmental variability within a field in order to determine whether a field scale or site specific management scheme is

best suited. A variety of tools are available to assess in-field variability. Some commonly available tools include yield maps, aerial photographs, and soil maps. Other tools such as remotely sensed NIR (near infrared) and RGB (Red, Green, Blue) imagery or the HMAP plant height measurement system offer alternative methods for assessing variability. The standard deviation of yield or plant height is one measure of the level of variability present. The Normalized Difference Vegetation Index (NDVI) calculated from NIR and RGB multi-spectral imagery is an example of another. Aerial photographs collected during bare soil conditions can be used to identify variable soil conditions within a field. While not always definitive, aerial photographs that show significant color variation across the field are often indicative of variable growing conditions within the field.

In addition to assessing spatial variability to determine optimal COTMAN management schemes, precision agriculture data sources can also be used to aid in selecting optimal COTMAN sampling schemes. An optimal sampling scheme is one that will adequately assess the general condition of the management zone (hereafter field) with a minimum number of samples. COTMAN recommends a minimum of four sampling locations for all fields and one site for each 4.0 hectares (10 acres) in fields larger than 16.2 hectares (40 acres). This article will present methodologies for spatially selecting optimal sampling schemes through the use of precision agriculture tools and a geographic information system (GIS).

MATERIALS AND METHODS

Test locations were selected from two distinct Texas growing regions with intense cotton production. One location was part of the Texas A&M University IMPACT Center located in Burleson County (Brazos River Valley of south-central Texas). Irrigated and dryland sites with .762 m (30 in.) row spacing were originally included from this location; however, poor establishment on the dryland site due to unseasonably dry conditions after planting negated its use. The irrigated site utilized a conventional center pivot irrigation system with rows oriented radially around the pivot that were managed with conventional tillage. The other location was in Wharton County on the coastal plains of south Texas. Irrigated and dryland sites with 1.016 m (40 in.) row spacing were utilized at this location. The Wharton County irrigated site used a conventional center pivot irrigation system coupled with furrow irrigation in corners. Straight rows and conventional tillage were used on both the irrigated and dryland fields.

Four sampling locations were chosen at each site by an experienced COTMAN scout. Two additional sampling locations were selected from the aerial imagery of each field in Digital Orthophoto Quarter Quad (DOQQ) format obtained from the Texas Natural Resource Information System (TNRIS) database. The additional locations were selected by identifying soil color areas not represented by the scout selected locations. The latitude and longitude of each sampling location was recorded with a differentially corrected Global Positioning System (GPS) receiver, and those same sites were

monitored with COTMAN for the entire growing season. Figure 1 shows the COTMAN sampling locations at the IMPACT Center and the DOQQ of the site.

Each field was monitored per COTMAN recommendations throughout the growing season. The monitoring sites were located by scouts for sampling via handheld differentially corrected GPS receivers. GPS was utilized to ensure that exactly the same locations were monitored each time data was collected. It also made it possible for different scouts to monitor the same fields in a consistent manner.

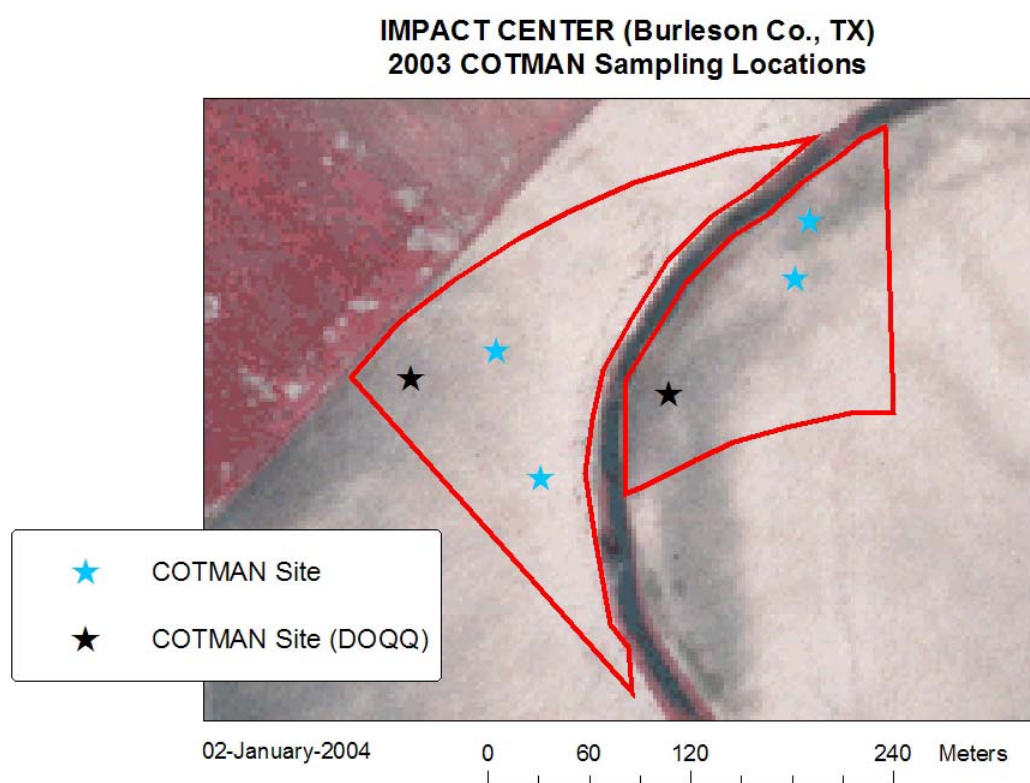


Figure 1: 2003 COTMAN Sampling Locations

Plant height was spatially recorded at each test field on approximately a bi-weekly basis throughout the growing season using the HMAP system. The HMAP system measures height using an industrial light curtain which consists of two parallel arrays of infrared emitters and receivers. Height is calculated from the number of blocked beams in the light curtain in a method described by Searcy and Beck (2000). The system utilized a tractor-based platform until cotton plants began to touch the axles and then was transferred onto a high clearance sprayer. Height was measured across two rows on the 1.02 m (40 in.) sites and across 4 rows on the .762 m (30 in.) site, the difference is attributed to implement configuration. Searcy and Beck (2000) verified that HMAP produces comparable results when measuring across 2 rows or 4 rows. Sampling passes were conducted every 18.29 m (60 ft) across the field consistent with the boom width of the sprayer and representative of routine field operations in production.

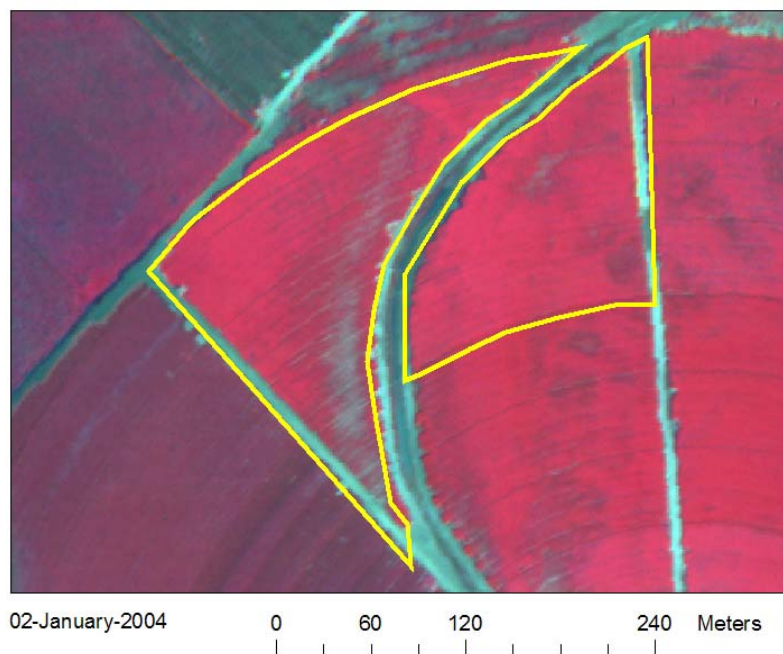
Multi-spectral NIR and RGB imagery was collected during the growing season by airplane as weather conditions permitted. Daily cloud cover made it difficult to collect timely high quality aerial imagery in this study; in the 2003 growing season imagery for two dates (July 25 and August 8) was obtained. These dates occurred after cutout (<5 NAWF) at both sites. The aerial imagery (one meter resolution) was collected and georeferenced by GeoVantage, a commercial aviation company. All Burleson County and Wharton County sites were included in the imagery. The imagery was post processed in GIS to generate maps of NDVI. Equation 1 was used to calculate NDVI. Several measures of NDVI have been suggested in literature; however, the one

calculated by Equation 1 is most prevalent (Tucker, 1979; Plant et al., 1999). Figure 2 shows NIR imagery and the NDVI map of the IMPACT Center in Burleson County.

$$1) \quad NDVI = \frac{NIR_{(Red)} - RGB_{(Red)}}{NIR_{(Red)} + RGB_{(Red)}}$$

Plant height data, field boundaries, DOQQ imagery, multi-spectral imagery, and sampling locations were compiled in a GIS for analysis. Figure 3 shows plant height values recorded at the irrigated fields in both Burleson and Wharton counties with the HMAP system. Each plant height data set was processed to identify the average height of the field and the standard deviation (σ) of height across the field. Plant height values within a finite range about the field mean were identified as average height locations for each sampling date. The range of height values classified as average varied relative to field variability while the number of locations remained constant by consistently identifying locations within $\pm \frac{1}{8} \sigma$ of the mean. Regions within each field that consistently (over multiple sampling dates) produced average height locations were identified as average height regions. Average height regions in this study were located by identifying (in the GIS) 12.19 m (40 ft) diameter circular regions in the field that contained at least one average height value from each date data was collected. Figure 4 shows average height locations and average height regions at the IMPACT center. The average height regions identified in Figure 4 are shown for illustrative purposes and do not represent the exact size or number of sites in this field.

IMPACT CENTER (Burleson Co., TX)
NIR Imagery: July 25, 2003



IMPACT CENTER (Burleson Co., TX)
NDVI: July 25, 2003

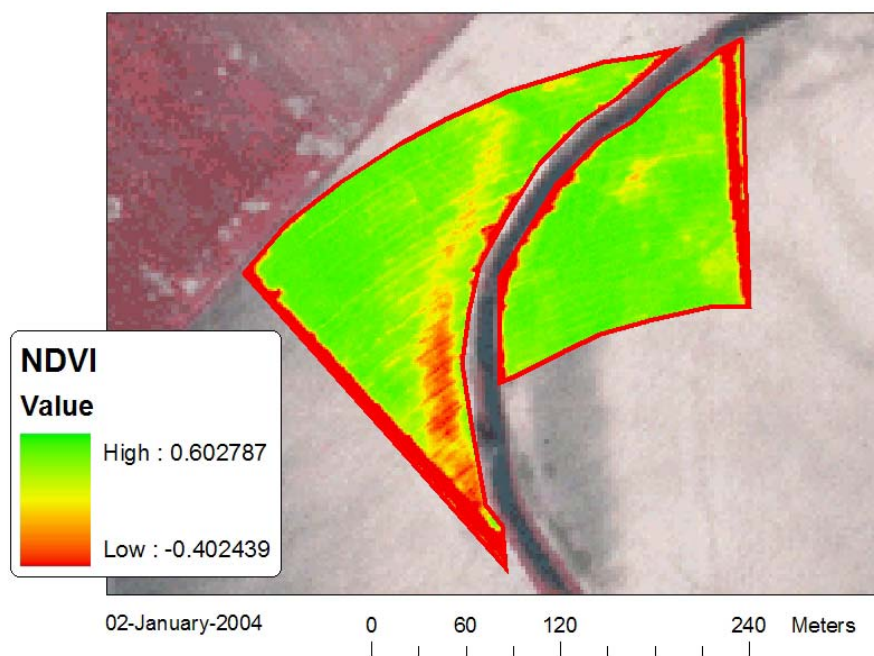


Figure 2: NIR and NDVI Maps

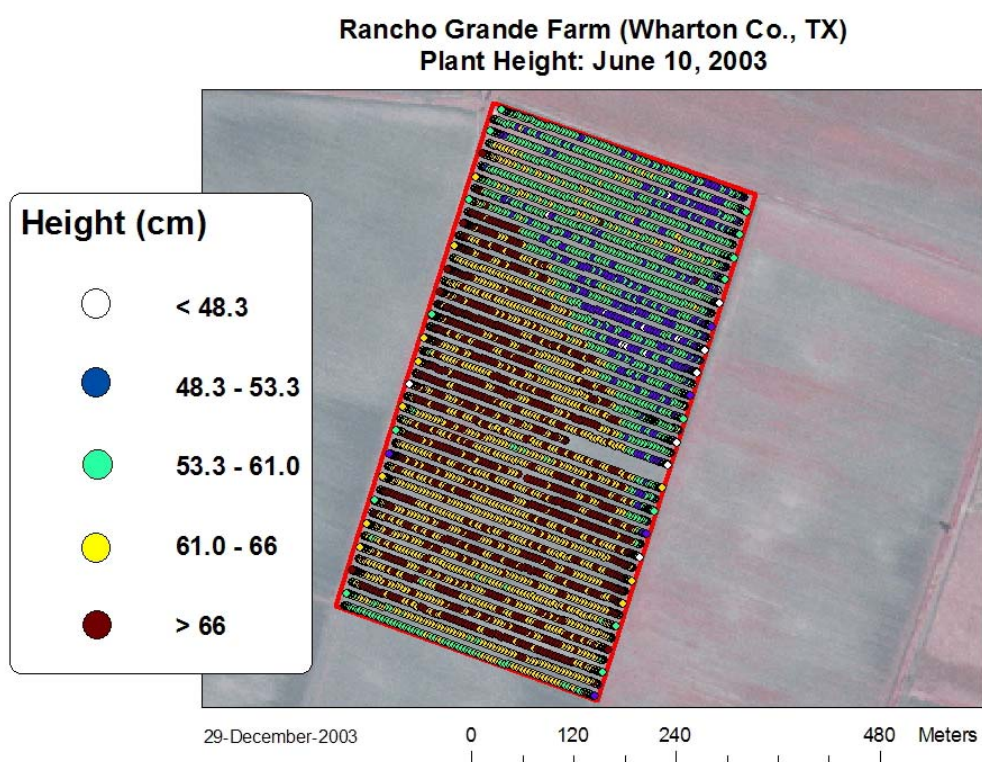
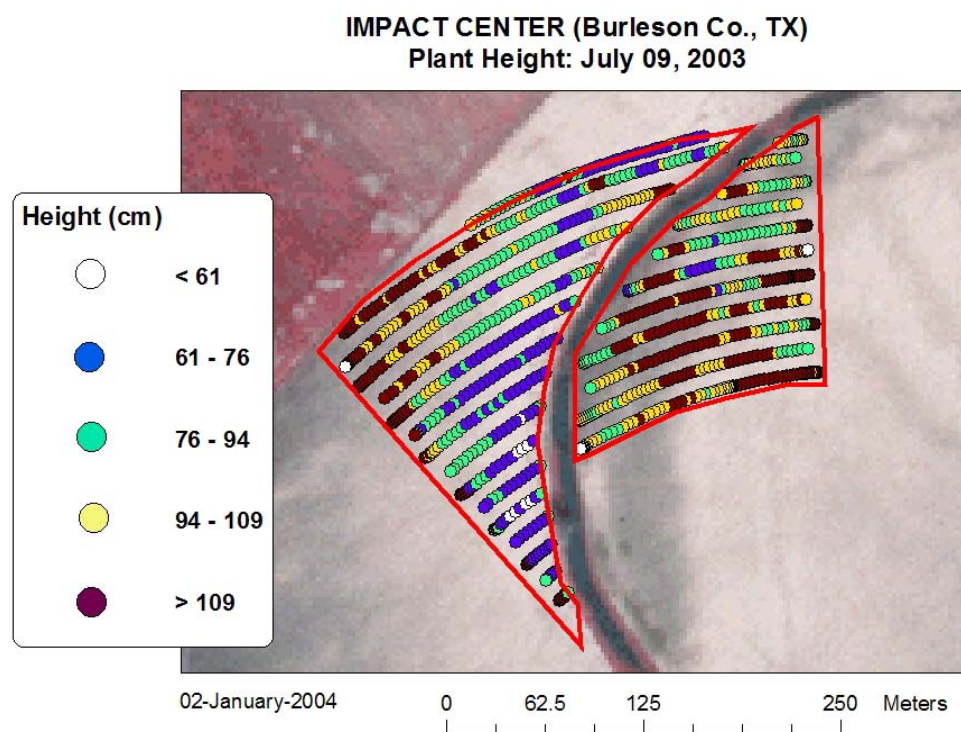


Figure 3: Plant Height Maps Created From HMAP Data

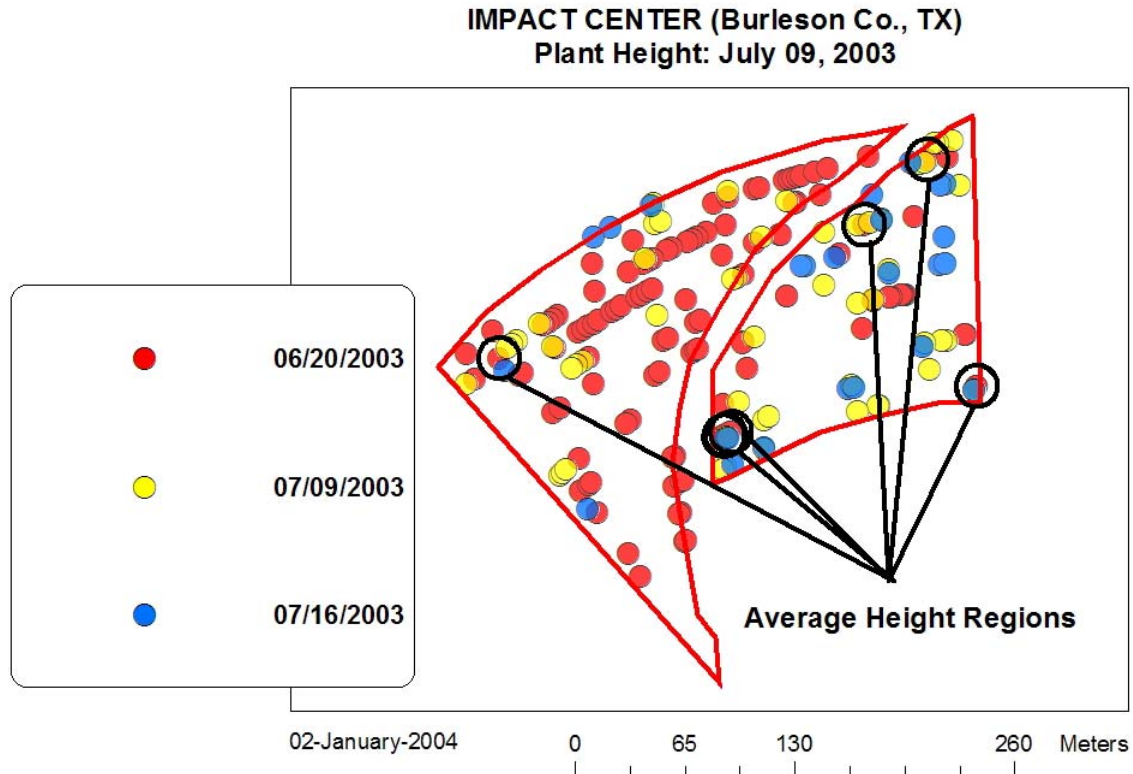


Figure 4: Average Height Locations and Regions

COTMAN analysis was conducted for each site in 3 variations using the following sample sets: all sampling locations, two sampling locations located in average height regions, single location with greatest variation from mean. Using all sampling locations represents the conventional use of COTMAN with the recommended sampling intensity. Using only two sampling sites represents the use of COTMAN with sites identified through height maps as representative of the field average. The single location represents the field region with the greatest deviation from the field average. The three nodes above first square and nodes above white flower (NAFS/NAWF) development

curves for each site were combined onto a single graphic for comparison. Figure 6 shows the NAFS/NAWF plots for the IMPACT center and the irrigated site in Wharton County.

Kerby and Hake (1996) suggested that vegetative growth rate can be determined by dividing the change in height over a time period by the change in number of nodes over the same time period giving units of length per node. In this study, rate of growth was calculated using Equation 2 giving units of length per day. Rate of growth maps were generated from the HMAP data for each height sampling field pass. Historical height data was interpolated in the GIS to generate a continuous surface of height across the field. A third degree inverse distance weighted (IDW) surface was used in this interpolation. IDW interpolation is widely used in agricultural applications and well suited for situations with a large distance between points (Kravchenko, 2003). Rate of growth at each point where height was measured on subsequent field passes was calculated using Equation 2. An example of a ROG map is show in Figure 5.

$$2) \text{ ROG} = \frac{\text{Height}_{\text{current}} - \text{Height}_{\text{historical}}}{\text{Time}}$$

RESULTS AND CONCLUSIONS

The test sites located in Wharton County can be classified as fields with little variability. Both the irrigated and dryland fields had a similar and consistent standard deviation of plant height throughout the growing season. The standard deviation of plant height in Wharton County ranged from 7.87 cm (3.1 in.) for the irrigated field early in the season to 11.68 cm (4.6 in.) for the dryland field late in the season. Table 2

summarizes the standard deviation of plant height on various dates for the Wharton County and Burleson County sites. Variations in the field that were expected to be present, such as the perimeter of the pivot sprinkler and the area not irrigated, are clearly evident in both the HMAP data and aerial imagery. NDVI maps generated from the imagery indicate that that the variation is subtle. Figure 3 clearly shows the boundary of the center pivot system.

Table 2: Standard Deviation of 2003 Plant Height Data (cm)

Location	Type	05/29/2003	06/10/2003	06/20/2003	07/03/2003	07/09/2003	07/16/2003
Wharton County	Irrigated	8.84	7.87	--	8.76	--	--
	Dryland	10.24	11.86	--	--	--	--
Burleson County	Irrigated	--	--	29.59	--	30.73	21.84

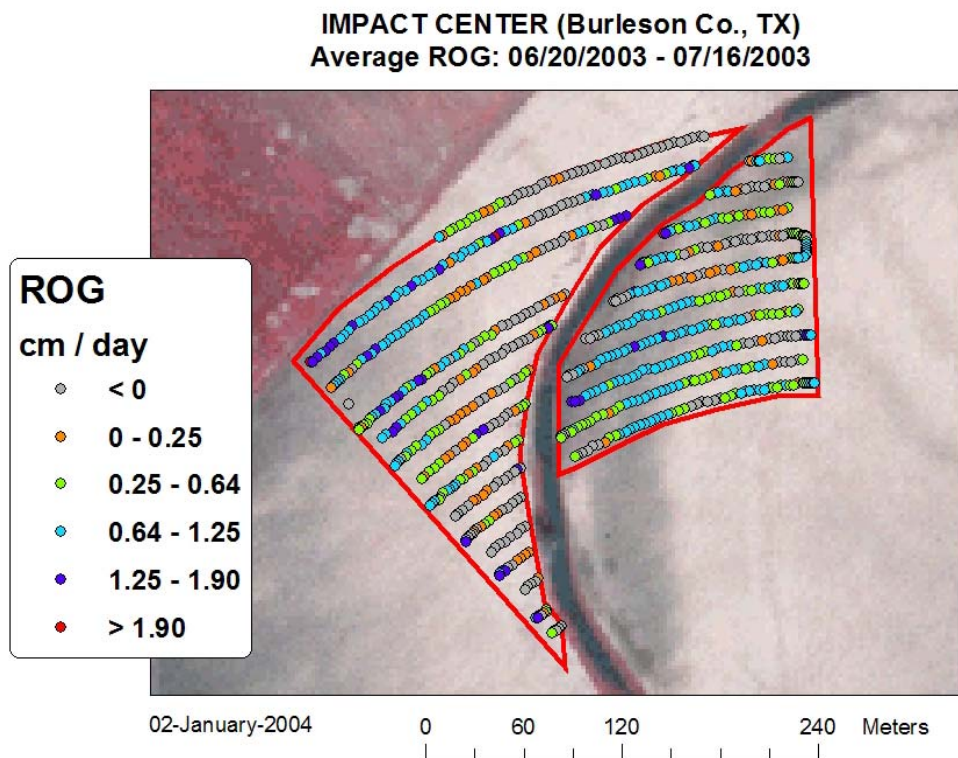


Figure 5: Rate of Growth Map

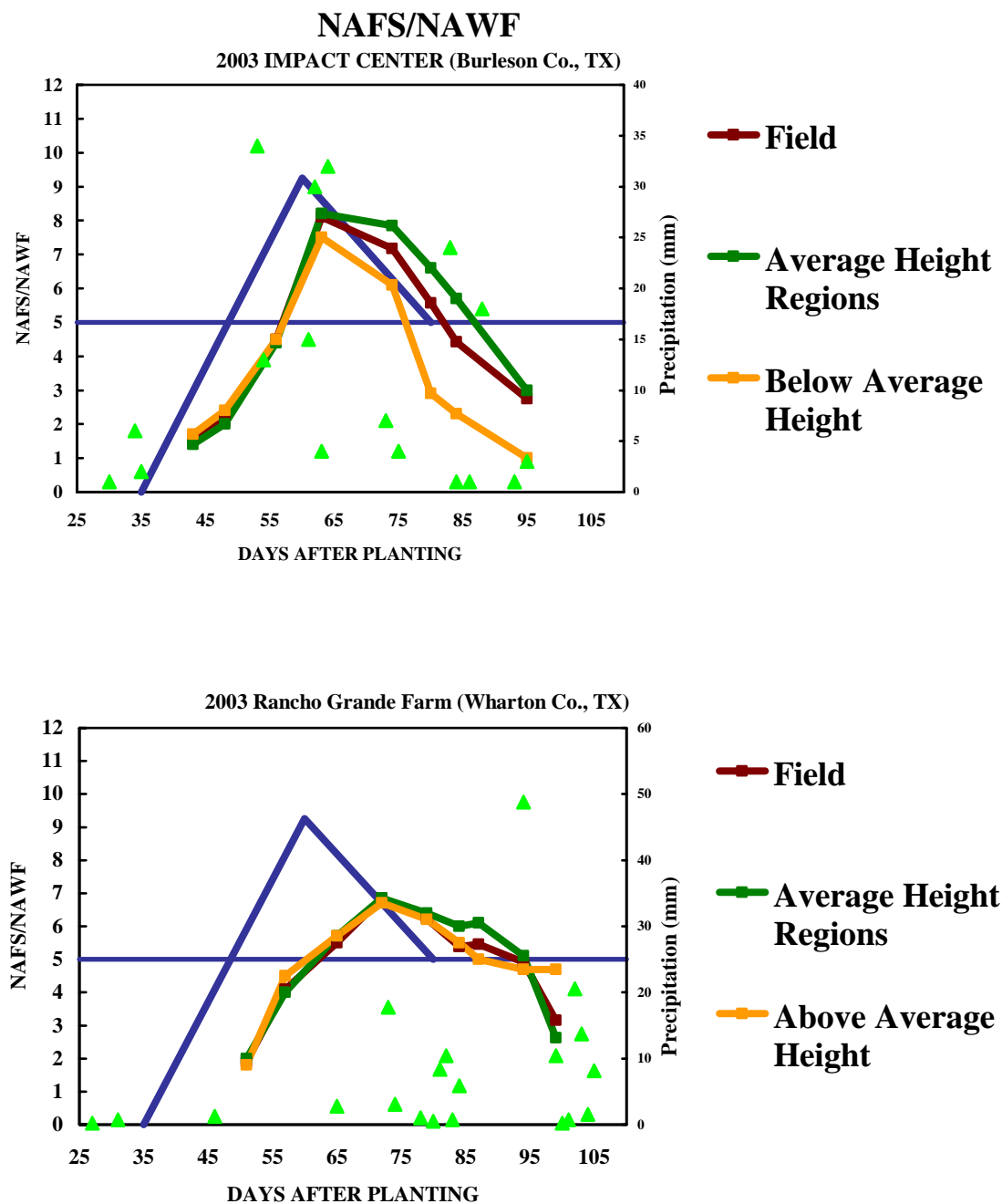


Figure 6: NAFS/NAWF Development Curves for Irrigated Sites
(triangles indicate rainfall events)

The IMPACT Center in Burleson County is an example of a field with significant variability. Variability at this site is clearly visible in the plant height maps, DOQQ imagery, NIR imagery and NDVI maps. The standard deviation of plant height at the irrigated Burleson County site was significantly higher than either of the Wharton County sites. The standard deviation ranged from 21.84 cm (8.6 in.) to 30.73 cm (12.1 in.) during the 2003 growing season. In addition, other precision agriculture data available for this site including yield maps, aerial imagery, soil conductivity maps, and soil series maps all indicate significant variability across the field. The Burleson County site would be more accurately managed by COTMAN if divided into smaller management regions. Significant variability is evident in all data sources considered in this study. While the focus of this study was to use the HMAP system in conjunction with COTMAN, data from other precision agriculture data sources would have led to similar conclusions pertaining to variability in this field.

The NAFS/NAWF curves for all fields show little difference between using two sites in consistently average regions versus using all sampling locations. There is somewhat less difference between the two curves in the Wharton County sites (<2 days difference in cutout) where little variability is present across the field compared to the Burleson County site (~5 days difference in cutout) with significant variability. It should be noted that using all sampling sites included those from the most variable sites and the most average. Therefore it is not surprising that the curve for all samples would fall between the curves for “most average” and “most variable”. The management recommendations from both SQUAREMAN and BOLLMAN (components of

COTMAN) are identical for all fields for “all samples” and “two most average” sampling strategies. Conversely, curves generated from a single site with greatest deviation from the mean were significantly different from the other two at all sites. The difference is greatest for the Burleson County site which is inherently due to the high degree of variability present at the site. COTMAN generates different management recommendations for the Burleson County site using a single site with greatest deviation from the mean.

Rate of growth maps show the same general variability trends as plant height maps, NDVI maps, yield maps, and aerial imagery. Some negative rate of growth values are present in all maps generated in this study. The negative values are generally located in areas of least vigor as identified in the NDVI maps. Fewer negative values are present when longer time intervals between height measurements are considered. Negative rate of growth values can be attributed to height measurement error and errors associated with surface interpolation in the GIS. The rate of growth map shown in Figure 5 contains the largest percentage of negative values of any map generated in this study. In this map, 26% of the calculated rate of growth values are negative; the negative values in this map have an average magnitude of -0.366 cm/day (-0.144 in/day). The rate of growth period spans a time period from just before cutout to just after cutout. The 2003 COTMAN data from this study showed that cutout in shorter less vigorous regions occurred in advance of the rest of the field. Therefore, the high percentage of negative values in this map is most likely the result of height measurement errors amplified by little or no change in plant height during the time period due to cutout. Overall, ROG

appears to be a powerful tool with potential to assess vegetative vigor across the field and provides information similar to NDVI.

SUMMARY

COTMAN generates uniquely different management recommendations within a particular field when regions of significant variability are considered separately. One of the sites used in this study had significant spatial variability while the other two sites had very little variability. Spatial variability can be quickly assessed by calculating the standard deviation of plant height. Machine measured plant height data can be used to identify average height regions which can be used to select optimal COTMAN sampling locations. In all sites considered in this study, irrespective of variability, the same management information was obtained from COTMAN by using two carefully selected sampling locations in place of many sites as recommended by COTMAN. Rate of growth can be calculated by comparing plant height data from multiple dates. NDVI maps used to assess vegetative vigor show the same general trends as rate of growth maps derived from plant height data.

CONCLUSIONS

This study suggests that COTMAN can be successfully implemented by conducting field scouting at significantly less sites than recommended by COTMAN. Precision agriculture and GIS provide a means to design improved COTMAN sampling schemes. Reduced field scouting directly translates into less input costs for producers.

In this study, rate of growth was calculated by post processing data in a GIS. Enhancements currently under way for the HMAP system will make it possible to calculate rate of growth in real time. Future research in conjunction with agronomists to develop target rate of growth curves for cotton may allow rate of growth information to completely replace a portion of the frequent crop scouting currently required by COTMAN.

ADDITIONAL DETAILS

Plant height data for this research was collected using the HMAP system. Figure 7 shows the basic components that make up the system. The Banner® MINI-ARRAY® scans the array at 200 Hz identifying blocked beams on each scan. HMAP software

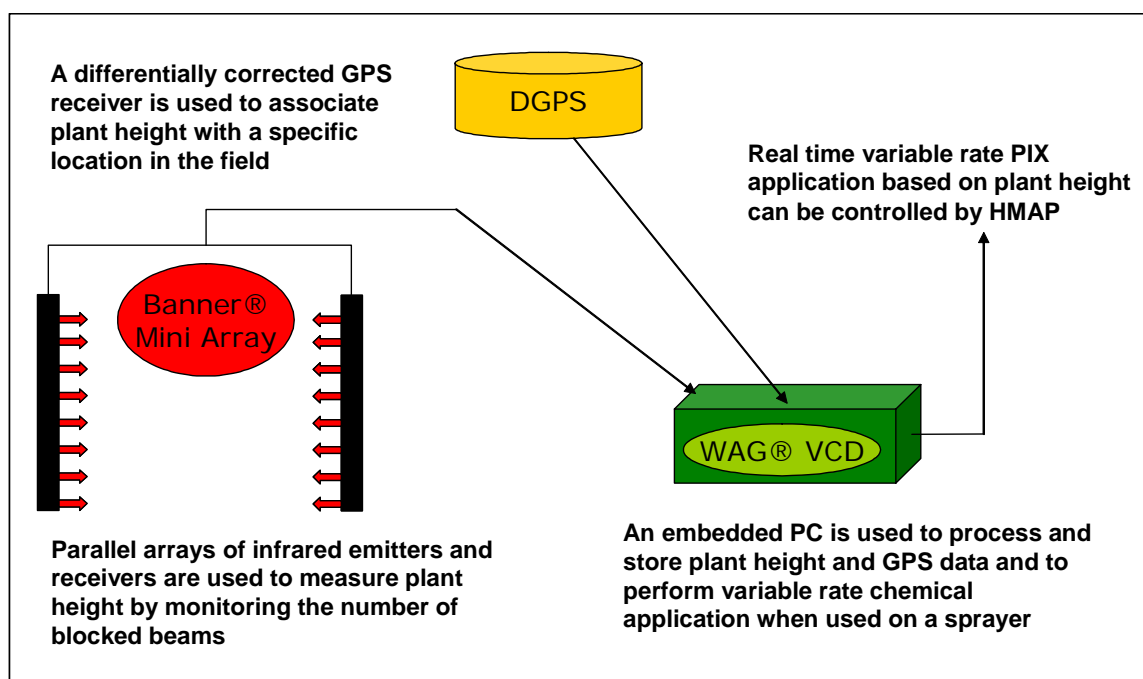


Figure 7: Basic Components of the HMAP System

determines plant height by building a histogram of incoming blocked beam data. Plant height is calculated as the value half way between 80% of the maximum detected height and 20% of the maximum detected height as described by Searcy and Beck (2000). The DGPS receiver used in this study was a Trimble® AgGPS® 114 with stated sub-meter accuracy. The DGPS position is recorded along with calculated plant height once per second by the HMAP system. The platform for the HMAP system is a WAG® Vision Computer Display (VCD) (originally developed by Rockwell Collins® as the Vision system) which consists of a MS-DOS based industrial PC and LCD display housed in a ruggedized enclosure. The HMAP software is written in Borland® C++. Technical details of select components of the HMAP system relating to height measurement are summarized in Table 3.

Table 3: HMAP System Height Measurement Component Summary

COMPONENT	PROPERTY	DESCRIPTION
Banner® MINI-ARRAY®	Model	BMEL3016A (Emitter) BMRL3016A (Receiver)
	Number of Beams	40
	Beam Spacing	0.75 in
	Output	RS-232 Serial
Trimble® AgGPS®	Model	114
	Accuracy	Sub-meter
	Correction	WAAS/EGNOS
	Update Rate (Maximum)	10 Hz
	Output	RS-232 Serial
WAG® VCD	Model	VCD
	Motherboard	Octagon Systems Corp.® PC-325R
	CPU	80486SLC
	Platform	MS-DOS
	Input	(4) DB9 Serial

Spatial data was analyzed using ESRI® ArcGIS Version 8.3. All data was projected to Universal Transverse Mercator, North American Datum 1983 (UTM, NAD83) for processing. COTMAN sampling locations recorded with differentially corrected Lowrance® iFinder handheld GPS receivers were converted from NAD (1927) to NAD83 using the NADCON conversion.

Two different procedures were implemented for identifying average height regions. In both procedures, average height locations for each date were identified as previously described and exported to a new (ESRI®) shape file consisting only of average height locations. The first method consisted of using the “Select By Location” feature in ArcGIS to identify points in other layers (average height locations from other dates) within a specified distance of points in the base layer (average height locations from the first date). This method ensured that consistently average height regions contained at least one average height location from each date data was collected. The second method involved using a script called “Nearest Feature” downloaded from the ESRI website (shareware, available from the author on request) to identify points from the base layer that were nearest to points in the other layers. Points in the base layer closest to points the other layers were identified as the centroids of consistently average height regions. Both methods produced similar results. The first method used built-in features of ArcGIS and was thus used in analysis of all field data in this experiment. The second method was used primarily to verify the results of the first method and was presented in this context as an alternative to ascertain the same information. The size of an average height region was assumed to be a circle with a 12.19 m (40 ft) diameter. An optimal

size for an average height region has not yet been determined by field trials; in this study the 12.19 m (40 ft) diameter size provided a small enough area to consistently identify plants representative of the field average and was large enough to make locating the region and collecting samples convenient. A detailed summary of the procedure for identifying average height regions in ArcGIS 8.3 is included in Appendix B for reference.

RECOMMENDATIONS FOR FUTURE COTMAN RESEARCH

The information obtained from one season worth of plant height and COTMAN data collected in this study indicates that field samples collected from two average height regions can be used to characterize a field for COTMAN in place of 4 to 6 sites as recommended by COTMAN guidelines. Further studies need to be conducted to verify that the relationship between average height regions and plants representative of the field average remains valid over multiple growing seasons. Analysis of cotton yield data has shown that yield regions (low, average, and high) generally remain consistent from season to season; it is hypothesized that plant height and average height regions follow the same pattern. Future studies could address whether once determined, average height regions can be used over multiple seasons to characterize the average conditions of the field. Such knowledge could make it possible for height data to be collected and analyzed during a single season and hence, allow producers without continuous access to a ground-based height mapping system to experience the same COTMAN sampling efficiency improvements as those with access to such a system.

This research briefly addressed the concept of selecting appropriate management zones for COTMAN. While it was shown that fields with a high degree of spatial variability exhibit large standard deviations of plant height when compared to fields with little variability, selecting specific management zones and classifying what constitutes a large standard deviation of plant height was not directly addressed. The development of

a decision support system for plant height data that aids in the selection of optimal management regions would further expand the utility of plant height data.

The concept of monitoring crop growth rate with respect to plant height or plant biomass was presented in the Introduction. In this research, COTMAN was used to monitor crop growth rate and plant height was used to aid in selecting optimal sampling schemes for COTMAN. Future research by agronomists could lead to the development of target plant height growth curves based on heat unit accumulation and historical climatic data similar to those generated by COTMAN which could be combined with current plant height data to directly track cotton development.

The optimal size for a consistently average height region has not been determined. Field trials with average height regions of different sizes would need to be conducted in order to define an optimal size. Regions with the largest possible size to adequately represent the field average would be most convenient by providing a large number of plants from which crop scouts could select samples.

REAL TIME RATE OF GROWTH DETERMINATION

INTRODUCTION

The concept of calculating rate of growth from current and historical plant height data was presented briefly in the previous article. Plant height data collected in 2001 and 2003 was used to validate the feasibility of calculating rate of growth by comparing height data from different dates in a GIS. While the concept seems relatively simple and straight forward, many factors are involved that makes it less than trivial. First, plant height data is collected by the sprayer-based HMAP system at discrete points in passes separated by 18.29 m (60 ft). In an ideal model, data would be collected from pass to pass at exactly the same points; however, if the implement driver was capable of driving down exactly the same path from pass to pass, even the best real time kinematic GPS receivers available lack the precision to locate exactly the same point in space twice. Further, the HMAP system calculates height by building a histogram of several height measurements accumulated over a 1 second time interval and thus, each recorded height value is a representation of a small region rather than a single measurement. This makes it necessary to build a continuous surface of historical plant height values from which to compare current values. Second, detecting small changes in plant height is difficult due to variable field conditions. The absolute magnitude of plant height changes over a small time interval is finite. Plant growth regulators and insecticides are applied frequently, often on an interval of 7 to 14 days. Variable field conditions such as irrigation or tillage, can cause vertical changes for the sprayer greater in magnitude than

plant height change on a small time interval. Factors such as wind or heat can also make a difference in height change detection when plants lean or leaves wilt. Third, inherent errors from all of the systems are compounded when comparing data from multiple dates. Each component has an associated error; when data from two dates is compared, errors can compound in an unpredictable manner. Despite these challenges, analysis of GIS calculated rate of growth data has shown that the concept is feasible and has the ability to accurately identify developmental variability across the field.

Ultimately, rate of growth data can be used to improve spray efficiency and effectiveness, particularly of plant growth regulators. Post processing plant height data in a GIS to determine rate of growth is a reasonable way to validate a concept for research purposes; however, to be practical for production, it must be determined automatically and in real time. While post processed data could theoretically be used to generate prescription maps for variable rate spraying, it would require twice as many field passes; one to measure plant height and one to spray with an intermediate step to process the data. Extra field passes are time consuming, expensive, and unnecessary.

The HMAP system offers a platform and software structure conducive to calculating rate of growth in real time. The components needed to measure plant height, spatial location, and to record data are already in place. A means to obtain historical plant height values at the same locations where current height values are recorded and a method to compare the current height values to historical values are the only additional functionalities needed to determine rate of growth in real time with the HMAP system.

The remainder of this article will detail the development and verification of an enhanced version of the HMAP system with the ability to determine rate of growth in real time.

MATERIALS AND METHODS

ADDITIONAL COMPONENTS

The basic components of the HMAP system were described in the previous article; Figure 7 and Table 3 summarize the basic components of the system. The VCD offers some computational resources for adding additional functionalities to the HMAP system; however, CPU usage is nearly maximized by the operations needed to maintain the current functionality. Continually processing a data set of historical height values each time current height is measured is computationally intensive and thus an additional CPU was added to the system to handle processing the historical height data. A Microsoft® Pocket PC 2002 based Hewlett-Packard® (hereafter, HP) iPAQ® (hereafter, iPAQ) model h3950 was selected as the hardware to handle this operation. A commercially available Pocket PC software package called Pocket Spreader v.1.35 (Delta Data Systems, Inc., Picayune MS) was selected to handle the data processing. Pocket Spreader is normally used to read prescription maps and control variable rate application systems; however, in this application it is used to read prescription maps of historical plant height and convey historical height data to the HMAP system. The iPAQ comes equipped with a single serial port while the Pocket Spreader requires two ports, one for GPS input and the other for output. A port expansion pack (HP P\N 173397-002) was added to the iPAQ to add a compact flash (CF) PC card slot. A ruggedized CF serial

port card (Socket Communications, Inc., Newark CA) was added to provide the additional serial communication port. A serial “Y” cable was constructed to allow the current GPS receiver to communicate simultaneously with both Pocket Spreader and the iPAQ at the same time. The “Y” cable eliminates the positional errors associated with using two separate GPS receivers. Table 4 summarizes the additional hardware and software components added to the HMAP system for rate of growth determination.

Table 4: Summary of Additional Components Added to HMAP for ROG Determination

COMPONENT	ITEM	DESCRIPTION
HP iPAQ	Model	h3950
	Memory	32 MB (ROM) 64 MB (RAM)
	CPU	400 MHz Intel®
	Platform	Pocket PC 2002
	Input	(1) DB9 Serial (1) USB
HP Expansion Pack	Model	173397-002
	Input	(1) CF
Socket Communications Ruggedized Serial Card	Model	SL2703-138
	Input	(1) DB9 Serial
Pocket Spreader	Version	1.35
	Platform	Pocket PC
	Output	ASCII String
	Map File Format	*.vaf
Serial “Y” Cable	Input	(1) DB9 Male
	Output	(1) DB9 Male (Null Modem) (1) DB9 Female (Standard)

All of the added components with the exception of the “Y” cable were purchased complete and required no special modification. The “Y” cable is unique in that it must provide standard RS-232 communication (Rx to Rx and Tx to Tx) between the GPS (Data Communications Equipment (DCE) device) and VCD (Data Terminal Equipment (DTE) device) and a modified null-modem RS-232 communication (Tx to Rx, Rx to Tx,

Request to Send (RTS) to Clear to Send (CTS), and CTS to RTS) between the GPS and iPAQ (DTE Device). Figure 8 shows the pin assignments and wiring schematic for the “Y” cable.

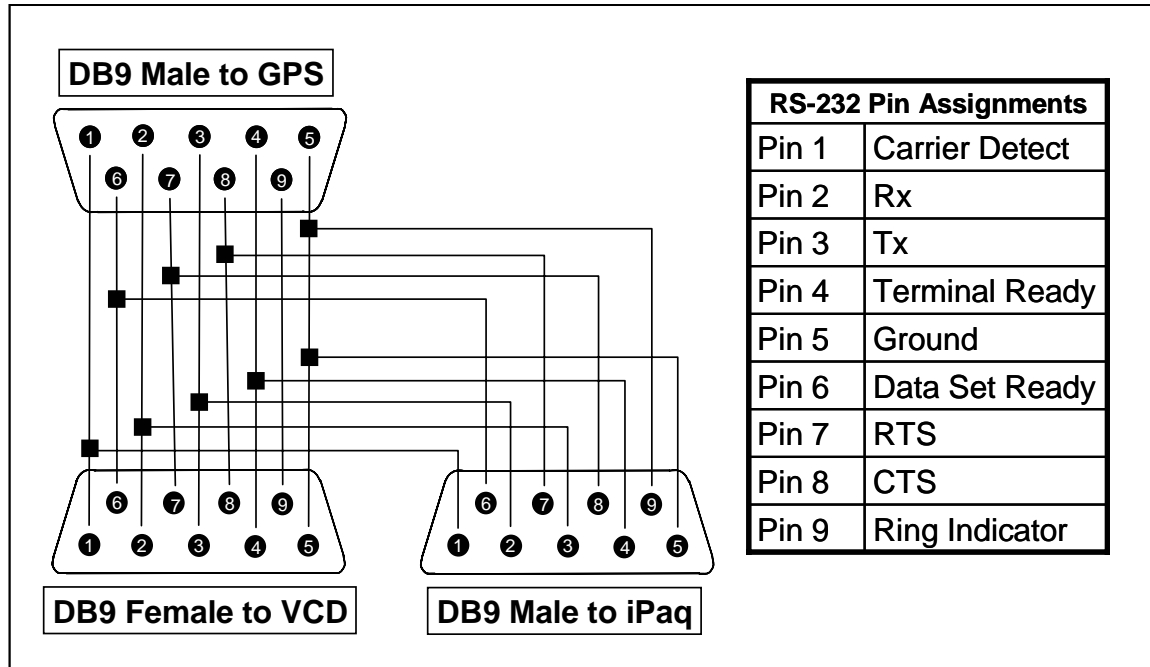


Figure 8: Serial "Y" Cable Wiring Diagram and Pin Assignments

SOFTWARE CHANGES

Extensive modifications to the current HMAP software were needed to interpret the historical height data, calculate rate of growth, provide an output to the operator, and log historical rate of growth and height data. A brief summary of changes is presented. Specific changes are noted in the source code which is available from the author on request.

First, the current software was upgraded from Borland® Turbo C++ v.1.0 to Borland® C++ v.5.2. While v.5.2 is not current software, it is the last Borland® compiler with the ability to generate 16-bit MS DOS code as required by the VCD. These changes primarily consisted of changing function calls for serial communication routines from CommTools v.1 (Magna Carta Software, Inc., Plano TX) functions to CommTools v.3 functions.

Second, new functions and objects were added to the HMAP code to handle requesting new data from the iPAQ and interpreting incoming data. Pocket Spreader believes that it is connected to a Raven® (hereafter Raven) 750 sprayer controller. When it receives an “actual rate” string (from the Raven or in this case the VCD) it generates and outputs a “rate calibration” string from prescription map data. New functions were developed in HMAP to generate “actual rate” strings and interpret “rate calibration” strings. Table 5 shows the ASCII format of the Raven strings. Each “product” in the “rate calibration” string represents one data layer in the prescription map being interpreted by Pocket Spreader. In HMAP, historical height values are the only data layer and are handled as “product 1”. A false “actual rate” string is sent to the iPAQ each time new historical height data value is requested. New data is requested once per second (the current recording rate of HMAP). An unreasonable value is sent to the iPAQ as the false “actual rate” to allow the operator to verify that communication is taking place from the VCD to the iPAQ; “actual rate” is displayed on the screen in Pocket Spreader (default is 0.0). A similar check is implemented on the VCD by not displaying historical height or rate of growth data unless the iPAQ is connected.

Table 5: Raven Strings Used by HMAP

STRING TYPE	ITEM	STRING EXAMPLE
Actual Rate (AR)	Format	\$R014,AR,<AR_1>, <AR_2>, <AR_3>,<AR_4>,<AR_5><CR><LF>
	Example	\$R014,AR,500,,,,<CR><LF>
	Interpretation	Raven Chip#: 014 Software Revision: D Actual Rate: 50.0,0,0,0,0
Rate Calibration (RC)	Format	\$R,RC,<RC_1>,<RC_2>,<RC_3>,<RC_4>,<RC_5><CR><LF>
	Example	\$R,RC,25,,,,<CR><LF>
	Interpretation	Change Rate to: 2.5,0,0,0,0

Third, user interface, data recording, and calculation functions were updated to include historical height and rate of growth data. When the system detects that both the height sensors and iPAQ are connected and transmitting data, rate of growth is calculated using Equation 2 (Page 20), historical height and rate of growth are displayed on the screen next to current plant height, and historical height and rate of growth are stored in the data file along with plant height, GPS coordinates, and other parameters. Constant parameters such as the number of days since historical data was recorded (used in rate of growth calculation) and the false actual rate value mentioned previously are stored in a user updatable initialization (*.ini) file which is automatically loaded at startup.

Fourth, the data processing program was updated to read the new data file format. HMAP data can be recorded in either binary or ASCII formats (user selectable). The binary format is preferred because less memory space is required to store binary data; however, it is completely useless without being processed. Data in either format is

recorded in HMAP line by line into a data (*.dat) file that must be interpreted and organized into a usable format. A program called Process (Process.exe, available from the author) is used to process recorded (*.dat) data into usable text (*.txt) and comma separated variable (*.csv) files. GIS software can directly read the *.csv file format. Changes were implemented to allow Process to read the new data generated by the rate of growth and historical height additions.

PREPARING HISTORICAL HEIGHT DATA

Before rate of growth can be calculated in HMAP, a preliminary data set of baseline height data must be collected during the first field pass of the season. Once the baseline height data is collected, each future field pass can use any previously recorded height values from the season as a source of historical height values. Previous discussion addressed the need to convert discrete plant height values into a continuous surface. It is therefore necessary to process historical plant height data into a continuous raster surface before attempting to determine rate of growth. Pocket Spreader reads a raster (prescription) map format called VAF (*.vaf). A GIS application called AGIS (Delta Data Systems, Inc., Picayune MS) is the only software package known that is capable of producing the VAF format. Continuous surfaces of 1 m resolution were generated in AGIS using a second order IDW interpolation method in this research. It should be noted that a third order IDW was used in GIS analysis of 2003 plant height data. This is due to differences in pass width; the field collected data required more “smoothing” due to a larger distance between passes. Interpolation parameters must change according to

the data source, details of the particular parameters used in testing of the real time rate of growth system are presented in the next sub-section. A detailed procedure for creating VAF files in AGIS is included in Appendix A for reference. The VAF file must be transferred onto the iPAQ and loaded into Pocket Spreader after it is created in AGIS. After a raster map is loaded into Pocket Spreader and the iPAQ, height sensors, and GPS are connected to the VCD, the HMAP system is ready to begin collecting and displaying height and rate of growth data.

TESTING THE SYSTEM

Preliminary testing of the rate of growth capable HMAP system was conducted on a test course at the Texas A&M University Agricultural Engineering Research Center in February 2004. The test course consisted of three 14.63 m (48 ft) runs made of 2.44 m (8 ft) sections ranging in height from .381 m to .635 m (15 in. to 25 in.) set on concrete 4.57 m (15 ft) apart. Figure 9 (not to scale) shows the test course setup. First, baseline height data was recorded. The varying height sections were assembled as shown in Figure 9 with the two shortest sections (same height) at the beginning followed by two intermediate sections and the two tallest sections (same height) at the end. Height was recorded on each of the three runs and each pass was made in the same direction at 3 mph. A surface of historical height values was generated from the baseline height data in AGIS.

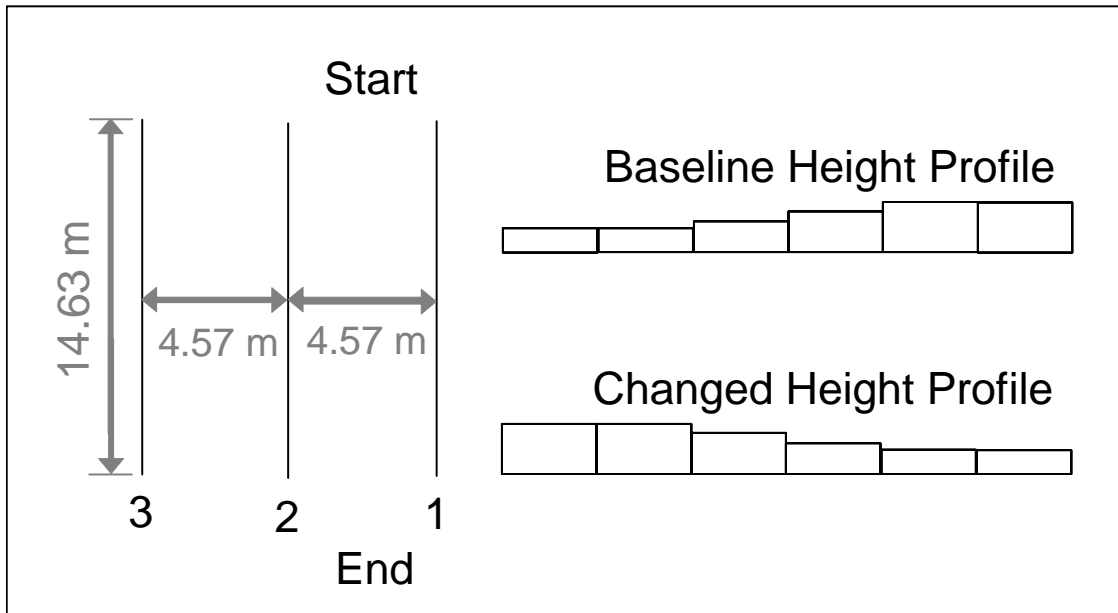


Figure 9: Test Course Setup

A second order IDW interpolation with a 12 m fixed radius of influence was used to interpolate a continuous surface at 1 m resolution. The VAF file created in AGIS was loaded onto the iPAQ and into Pocket Spreader. The height sections were re-arranged to the changed height profile shown in Figure 9. An arbitrary value of 10 days was used as the time interval between height measurements. Data was collected during 10 trials on the test course. Each trial consisted of 3 passes always moving in the same direction as the baseline height data was recorded. The HMAP system was shut down and the data card was cleared between trials to ensure that each trial was unique.

DATA PROCESSING

The recorded data was loaded into ArcGIS for processing. Data was analyzed in two variations: 1) zero height values recorded at the beginning and end of each run

(where no height sections were located) were removed from the data set, 2) zero height values were included. Each data set was converted to a raster (ESRI Grid) format for GIS analysis. A new surface was generated from the baseline height data in ArcGIS using the same interpolation method and parameters as in AGIS. This step was necessary because the VAF format is not compatible with ArcGIS. A theoretical height change was calculated for each data point by subtracting the raster values from the continuous surface of baseline height from the HMAP measured height. Rate of growth is the desired output from this research; however, rate of growth is a relative calculation with a magnitude dependent upon the number of days between data sets whereas height change is absolute. The theoretical height change was subtracted from the HMAP calculated rate of growth multiplied by 10 (the arbitrary number of days) to identify the error in height change estimation associated with each data point.

The height change error data was exported into the statistical software package SPSS for further analysis. A one way analysis of variance (ANOVA) was conducted to determine if the mean error in detected height change was significantly different between trials at a 95% confidence interval. In addition, a Games-Howell multiple comparison test was conducted to identify significant differences in means between individual trials.

RESULTS AND CONCLUSIONS

The HMAP system functions well with the added rate of growth determination features. Historical height values displayed on the HMAP screen match values displayed on the iPAQ in Pocket Spreader indicating that data is being transferred between the two devices accurately and in a timely manner. The displayed and recorded rate of growth values vary as intended relative to height changes detected by the system indicating that the HMAP software is working properly.

Analysis of data collected on the test course indicates that the system has a mean height change detection error of +3.43 cm (+1.35 in.) when zero height values at the beginning and end of test runs are removed and 2.36 cm (+0.93 in.) when zero values are included. While the zero values are real values recorded with the system, they only exist outside of the test area and do not contribute to the desired rate of growth parameter; therefore, only the variation where zero values were removed will be considered hereafter. The ANOVA analysis revealed no significant difference in means (of height change detection error) between trials with significance of 0.831 at a 0.05 confidence level. Table 6 contains a statistical summary of the test course data. The Games-Howell multiple comparison test confirmed that the mean height change detection error of each individual trial was not significantly different from the mean of any other trial. Table 7 shows the significance values from the Games-Howell test. Very high significance values give a strong indication that none of the means are significantly different.

The height change detection error was somewhat higher than expected. A variety of factors may be contributing to the calculated error. Test course data was collected using

a continuous surface generated in AGIS while the theoretical height change was calculated using a continuous surface generated in ArcGIS. While the IDW interpolation parameters were identical and the same set of discrete data was used to generate both surfaces, it is probable that the surfaces are not exactly the same due to differences in the algorithms between the two GIS packages. The test course consisted of both positive and negative height changes equal in magnitude; thus, the ideal model would have a height change detection error of zero. The positive mean error is a strong indicator that the baseline height surfaces may not be exactly the same. Another contributing factor may be the resolution of the rasterized height data; a one-meter resolution surface was used in this study. The HMAP system records rate of growth once every second; at 1.34 m/s (3 mph) one to three different height values may be read from the one-meter resolution surface while only a single value is recorded. While changes are not generally abrupt on an interpolated surface, this may also be a factor contributing to the higher than expected error. Historical height values output by Pocket Spreader have a precision of 1; thus, all values from the continuous surface are subject to rounding. All of the errors are compounded when using a relatively small test course. The HMAP system is designed to be used on a field scale. In field conditions, plant height normally does not change as abruptly or as frequently as on the test course. In addition, the data sets considered in this study (<50 data points per trial) are extremely small compared to field size data sets.

The largest contributor to the mean height change detection error is most likely the difference in interpolated surfaces between AGIS and ArcGIS. A random sampling of

like points (1 m x 1 m grid cells) in ArcGIS and AGIS confirmed that interpolated values differ slightly between the two surfaces. Therefore, the true error may actually be less than reported in this article. The high significance value from the ANOVA analysis testing for differences between dataset means indicates that the system performs in a consistent and repeatable manner. Even with a mean height change detection error of 3.43 cm (1.35 in.), the system is still capable of providing useful and timely data. Future field testing will be required to validate the true accuracy and usefulness on a field scale.

Table 6: Summary of Height Change Detection Error Analysis

General Statistics			
Trial	N	Mean	Std. Deviation
1	37	3.41125	3.42235
2	38	3.07442	3.24968
3	32	4.10235	2.20424
4	28	3.43365	3.47431
5	26	2.78211	3.90398
6	28	3.36944	3.54477
7	32	3.98290	2.55618
8	33	3.13682	3.42356
9	31	3.19364	2.55763
10	25	3.83703	2.32214
TOTAL	310	3.42915	3.09570

ANOVA					
	Sum of Squares	df	Mean Square	F	Sig.
Between Trials	48.793	9	2.1336	.558	.831
Within Trials	2912.478	300	3.8227		
TOTAL	2961.271	309			

Table 7: Significance* Value Summary from Games-Howell Test

Trial	1	2	3	4	5	6	7	8	9	10
1		>.999	.991	>.999	>.999	>.999	.998	>.999	>.999	>.999
2	>.999		.858	>.999	>.999	>.999	.948	>.999	>.999	.984
3	.991	.858		.996	.868	.994	>.999	.935	.883	>.999
4	>.999	>.999	.996		>.999	>.999	.999	>.999	>.999	>.999
5	>.999	>.999	.868	>.999		>.999	.935	>.999	>.999	.972
6	>.999	>.999	.994	>.999	>.999		.999	>.999	>.999	>.999
7	.998	.948	>.999	.999	.935	.999		.979	.965	>.999
8	>.999	>.999	.935	>.999	>.999	>.999	.979		>.999	.995
9	>.999	>.999	.883	>.999	>.999	>.999	.965	>.999		.992
10	>.999	.984	>.999	>.999	.972	>.999	>.999	.995	.992	

*significance values greater than .05 indicate means are not significantly different at a 95% confidence level

SUMMARY

The concept of rate of growth determination was investigated by processing plant height data collected in 2003 in a GIS. The HMAP system was extended to add the functionality to calculate and record rate of growth in real time. The extended HMAP system was tested on a test course to validate function and repeatability. The accuracy of the rate of growth system as determined from test course data was somewhat higher than expected but was still within an acceptable range. Field testing is needed to validate the conclusions reached on the test course. Real time rate of growth determination offers a never before available means for monitoring cotton growth and development. It will be left to future research to find uses and applications for the technology that has been developed through this research effort.

RECOMMENDATIONS FOR FUTURE RATE OF GROWTH RESEARCH

The HMAP rate of growth system performed relatively well during preliminary testing on a test course with solid panels used to simulate plant heights. Field verification will be necessary to determine the accuracy of measuring rate of growth in real time in cotton. Field data will also allow parameters such as the resolution for an interpolated surface, interpolation method, and interpolation parameters to be optimized for field scale measurement of cotton.

Some examples of the potential utility of rate of growth data have been presented in the previous articles such as monitoring cotton growth and development and improving the efficiency and effectiveness of variable rate plant growth regulator application. It will be left to other engineers and agronomists to further develop applications of real time rate of growth and explore the physiological relationships between rate of growth and cotton development.

When used on a sprayer, the HMAP system is already capable of varying chemical application rates in real time based on plant height variation. Once relationships between rate of growth and need for growth regulator have been developed, it will be possible to further enhance the HMAP system by using the rate of growth data in addition to plant height data to calculate application rates. In addition, the iPAQ and Pocket Spreader software make it possible to read multiple prescription map layers at the same time (up to 5 layers). Refinements to the MEPRT program which currently uses only an average (field average) value of previous growth regulator could allow site

specific historical application data to be used when calculating applications rates. Other prescription map layers such as management zones where no growth regulator is desired could be added as well and used to turn the spraying system on and off automatically.

SUMMARY AND CONCLUSIONS

SUMMARY

The HMAP system, which uses machine based height sensors and a differentially corrected GPS receiver to spatially map plant height, was used to map cotton height at three test sites located in two distinct Texas growing regions during the 2003 growing season. The same sites were monitored via field collected data using the COTMAN expert system. Regions of each field that produced plants with a height equal to the field average on every field pass were identified and classified as average height regions. Field data collected from two average height region sampling locations was able to generate an equivalent COTMAN output as two to three times as many sites selected per COTMAN recommendations at all sites included in this study. A high degree of spatial variability within fields can be indicative of a need for site specific management. Spatial variability was evaluated by the standard deviation of plant height in this study. Fields with a large standard deviation of plant height also showed significant variability in NDVI maps generated from remotely sensed imagery.

Plant height data collected in 2003 was used to generate rate of growth maps in a GIS by comparing height measurements from multiple dates. This process requires the generation of a continuous surface of historical height values due to the fact that the HMAP system records height at discrete locations. Rate of growth maps were compared to NDVI maps which showed that high and low rate of growth values were closely aligned with high and low NDVI values.

The HMAP system was extended to calculate rate of growth in real time. This was accomplished by integrating a Pocket PC based application capable of reading rasterized prescription maps of historical plant height values into the current HMAP system. Function of HMAP rate of growth system was verified on a test course consisting of panels of varying height. Statistical analysis of data collected on the test course revealed that the system performed consistently and in a repeatable manner.

CONCLUSIONS

1. Manual field sampling for COTMAN can be significantly reduced by selecting sampling locations from consistently average height regions.
2. Spatial variability within a field can be characterized by the standard deviation of plant height.
3. Vegetative vigor can be assessed by creating rate of growth maps from plant height data collected at different times.
4. The HMAP system can be used to calculate rate of growth in real time by comparing current height measurements to historical height values.

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APPENDIX A**PREPARING PRESCRIPTION MAPS OF HISTORICAL PLANT HEIGHT FOR
USE WITH HMAP**

PREPARING PRESCRIPTION MAPS OF HISTORICAL PLANT HEIGHT FOR USE WITH HMAP

INTRODUCTION

Historical plant height data must be converted to prescription map format prior to being used with *Pocket Spreader* and the *HMAP* system for ROG calculation. The following procedure describes the process of preparing prescription maps in detail. Similar procedures can be implemented with other data types to generate prescription maps of other parameters. *Pocket Spreader* is part of the Delta Data Systems (DDS) family of products. Currently, AGIS is the only software known to generate the VAF file format required by *Pocket Spreader*. The main focus of this discussion will be on using AGIS to prepare prescription maps. Because of limited functionality in AGIS, some procedures will also be described for ESRI *ArcGIS* 8.3.

FORMATTING DATA

Generating a text file or spreadsheet from raw HMAP data must be conducted prior to creating a prescription map of historical plant height. Software has been developed to convert HMAP data into a CSV format for GIS compatibility. A DOS based application called *Process* (available from the author) can be used to process binary data into comma separated text and GIS formatted text. The user interface for *Process* is simple and self explanatory. Currently, *Process* is configured to generate an *ArcGIS* compatible CSV format; slight modification of the CSV file is necessary for AGIS compatibility. The required CSV formats for *ArcGIS* and AGIS are described below.

ArcGIS allows comma separated “X,Y” data to be imported in the following format where at least two variables represent the X and Y coordinates:

```
Line 0:    var1_name,var2_name,varN_name <CR>
Line 1:    var1_1,var2_1,varN_1<CR>
Line 2:    var1_2,var2_2,varN_2<CR>
Line N:    var1_N,var2_N,varN_N<CR>
```

AGIS allows “point” data to be imported in several formats including comma separated variable format and Microsoft *Excel* spreadsheet format. The comma separated variable format for AGIS has the following format where at least 2 variables represent the X and Y coordinates:

```
Line 0:    var1_1,var2_1,varN_1<CR>
Line 1:    var1_2,var2_2,varN_2<CR>
```

Line N: var1_N,var2_N,varN_N<CR>

The main difference between *ArcGIS* and *AGIS* formats is the absence of the first line containing variable names in the *AGIS* format. *AGIS* also allows data to be imported as Excel spreadsheet data. Comma separated text files can be easily imported into *Excel* and quickly modified to conform to the *AGIS* format and saved as spreadsheet (.xls) files. The limitations of *Excel* are that data sets are limited to 60,000 lines and the software functions at a reduced speed when working with large data sets. Figure A1 shows an acceptable *Excel* format. When using *Excel* spreadsheets in *AGIS* it is acceptable to have variable names in the first row while when using text files it is not.

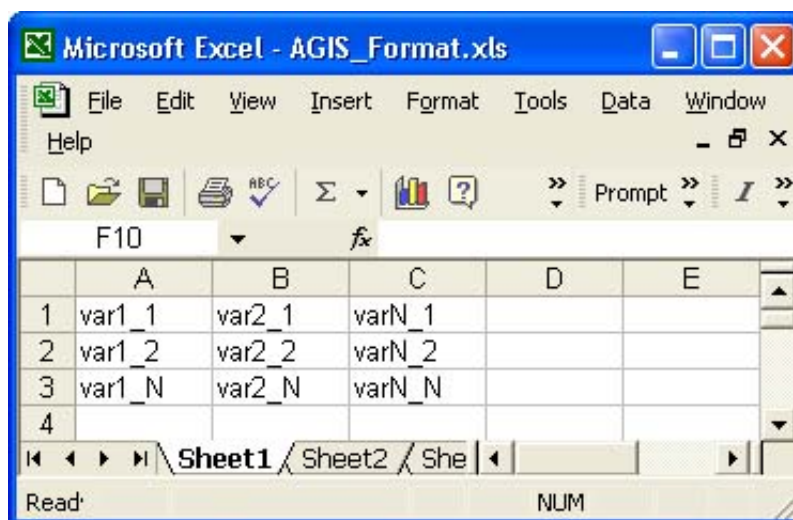


Figure A10: Excel Spreadsheet Format for AGIS

PREPARING DATA LAYERS

Prescription maps are created from interpolated surfaces generated from discrete data points. It is important for the interpolated surfaces to be contained within a field boundary because the accuracy of such a surface rapidly deteriorates when data points do not exist. *ArcGIS* was used in this research to create field boundaries. The following procedure can be used in *ArcGIS* to define field boundaries:

- 1) Load spatial reference data. This defines the projection and datum for the data layer in the map. Plant height data, aerial imagery, yield data, data points collected with a handheld GPS receiver or any other available data source can be used for this purpose. Load such data sources into a new map in *ArcGIS*.
- 2) Create new shape file. Before a field boundary can be drawn, it is necessary to define a shape file. This is accomplished using *ArcCatalog*. Open *ArcCatalog*

and in the desired directory click File -> New -> Shapefile which opens a “Create New Shapefile” dialog as shown in Figure A2. Enter a Name and select the Polygon Feature Type. Click the Edit button and define an appropriate coordinate system. This process is simplified if the desired coordinate system matches that of an existing data source. In this case select Import and select the data source from the directory. Otherwise, choose Select and follow the menus to select the desired coordinate system. Once the coordinate system has been defined, click OK to complete the shape file definition.

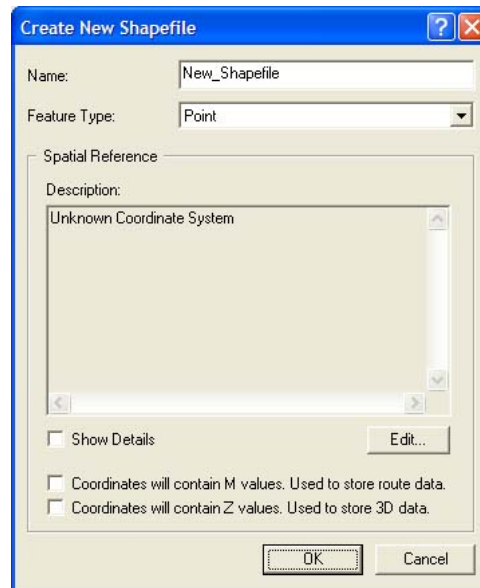




Figure A11: New Shapefile Dialog

- 3) Load new shapefile into *ArcGIS*. Click File -> Add Data or use the Add Data Button  and select the newly created shape file.
- 4) Sketch the field boundary. Ensure that the “Editor” toolbar is displayed and click Editor -> Start Editing. Ensure that the Target: selection is the new shape file. Ensure that the Task: is Create New Feature. Select the Sketch tool  and sketch the field boundary. When the boundary is complete, double click to complete the shape. If several fields are to be included in the data set, multiple polygons can be sketched.
- 5) Save the field boundary and export shape file. Click Editor -> Stop Editing and when prompted Save Edits. This shape file is normally ready to be used by other applications; however, to guarantee it, the field boundary should be exported as a new shape file. Right click on the field boundary in the Table of Contents and

click Data -> Export Data and save the new shape file to the desired location with the same coordinate system as the layer's source data.

ASSEMBLING DATA IN AGIS

Once a coordinate system has been defined in *AGIS*, it is not possible to change it in the future as is common practice in *ArcGIS*. Therefore, it is critically important to define the correct coordinate system when a new GIS is assembled. Much of the publicly available data sources in Texas such as DOQQ imagery use UTM Zone 14N NAD83 which conforms to the datum and projection used for the majority of GIS analysis in this research. The following procedure describes the process for creating establishing a coordinate system and loading data layers in *AGIS*:

- 1) Create Grower. Click Data -> Create Grower and enter a name. The term "grower" is analogous to "client" used in many other farming specific GIS software.
- 2) Create Farm and establish coordinate system. Click Data -> Create Farm and enter a name. Each farm can contain many fields. Click Next and select an appropriate season. Click Next and choose an appropriate pixel resolution. The default is a 5 meter by 5 meter resolution; however, a resolution appropriate for the data should be selected. Since the prescription map will ultimately be used with a Pocket PC where storage capacity is limited, a resolution no greater than 2.5 meters by 2.5 meters is recommended. Click Next and the projection dialog box will appear. Uncheck the box next to "Determine UTM zone from incoming field collected data". The default is UTM Zone 15N WGS 1984. If the desired coordinate system is different from the default, click Change Projection and select the desired datum and projection. Click Finish to complete the farm definition.
- 3) Import field boundary shape file. Click Tools -> Import Drawing -> Shape. This will launch the shape file import wizard. Select the field boundary created in *ArcGIS* (*.shx). Click Next and a projection dialog will open. Since *AGIS* does not recognize the full ESRI shape file format (*.shp) the projection information will have to be redefined. Click Select Projection and select the appropriate coordinate system for the field boundary. This must be the same datum and projection used previously in *ArcGIS* but does not have to be the same as the *AGIS* datum and projection; *AGIS* will project the selected coordinate system onto the Farm projection automatically. Click Next and select or create an appropriate layer and Field. Click Next and accept the default drawing file. Click Finish and the field boundary will be added as a layer. In order to display the field boundary, click the check box next to the layer name in the table of contents and click Apply.

USING INTERPOLATION TO GENERATE A CONTINUOUS SURFACE IN AGIS

Once the field boundary has been added to *AGIS*, it is possible to create an interpolated surface of plant height. The interpolation capabilities of *AGIS* are somewhat limiting; however, Inverse Distance Weighted (IDW) interpolation has been shown to produce acceptable accuracy. The following procedure describes the methodology for interpolating a continuous surface of plant height from discrete plant height data points in *AGIS*:

- 1) Launch the surface generator and define the field boundary. Click Tools -> Surface Generator and a surface generator application will appear. Within the application click Surface -> Boundary Objects and select the field boundary from the image. The color of the field boundary will change from blue to red when selected. Right click away from the boundary to end the selection process.
- 2) Import discrete data. As stated previously, point data can be imported into *AGIS* in several formats including text files and Excel spreadsheets. The Excel method is described here; however, the text file method is nearly identical. Click File -> Point File -> Excel (.xls) file and select the *Excel* spreadsheet file and worksheet that contain the plant height data. Deselect the box next to "First Row Contains Column Headings" if the spreadsheet was prepared using the methodology previously described. Click OK and select the appropriate datum and projection for the point data. Click Finish to launch the XLS Vertex Parameters dialog. Select the appropriate field names for the X and Y coordinates where, F1, F2, ..., FN correspond to the columns of the spreadsheet. Select the Z coordinate as the column that corresponds to the plant height data. Click OK, accept the default drawing file parameters and click OK to complete the import process.
- 3) Generate continuous surface of plant height. Click Surface -> Moving Average and select Inverse Distance Average (the default) and an appropriate decay constant and radius of influence. Click OK to launch the output file dialog. De-select the check box next to "Test" as surfaces generated in the test mode cannot be used later to create prescription maps. Select the appropriate resolution, Field Name, and Season and check the box next to "Preview Surface". A completed dialog box is shown in Figure A3. Click OK and approve the default surface channel selections in the dialog box. Click OK to accept the surface shown in the preview. The preview surface is not bound by the field boundary and is not in color; this will change after approving the surface build. Click File -> Exit to leave the surface generator application. Check the box next to the newly created layer in the table of contents and click Apply to display the interpolated surface.

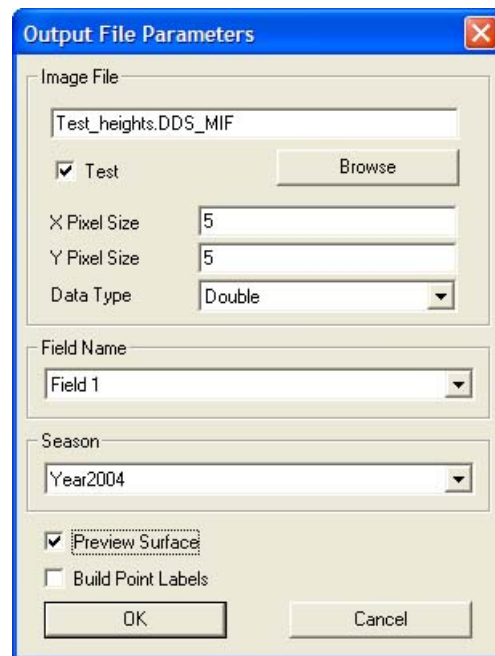
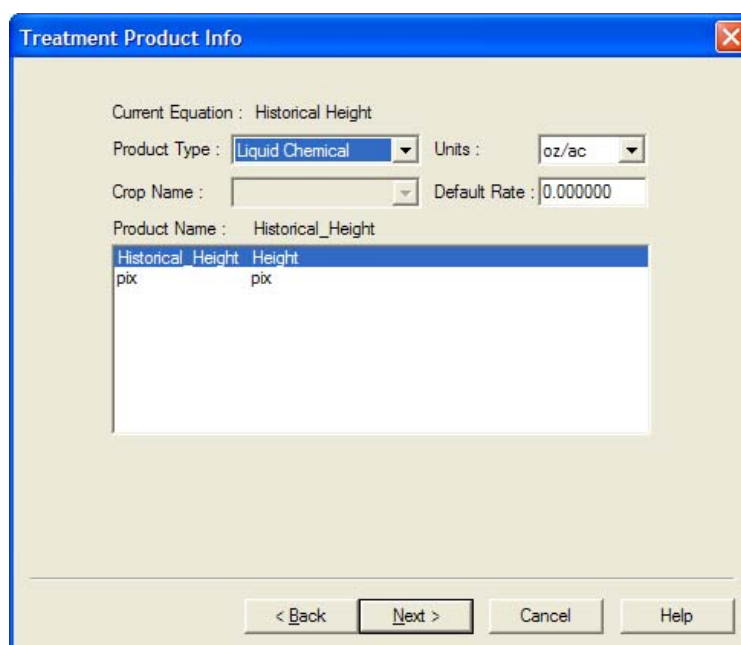


Figure A12: Completed Output File Dialog

CREATING A PRESCRIPTION MAP IN VAF FORMAT

After a continuous surface has been interpolated, it is necessary to create a “Treatment” map in VAF (*.vaf) format to be used in *Pocket Spreader*. The following procedure can be used to generate a “Treatment” map in *AGIS*:

- 1) Define Equation. Click Analysis -> Treatment. This will launch a treatment dialog. Here it is necessary to define or select an existing treatment equation. For the purposes of historical plant height, this is not very important as the interpolated surface pixel values are used directly to calculate the “Treatment”. In other cases, it may be necessary to equate application (“Treatment”) rate based on multiple map layers. For historical height, either define a new equation by clicking Add Equation... (necessary the first time a treatment map is generated in a new map layer) and follow the dialog or select an existing equation from the list. Click Next. This will prompt the dialog shown in Figure A4. Here it is necessary to select a product to apply. If no product has been previously defined, exit the dialog, follow the procedure below, and start over at 1); otherwise, skip ahead to step 2.



Treatment Product Info

Current Equation : Historical Height

Product Type : Liquid Chemical Units : oz/ac

Crop Name : Default Rate : 0.000000

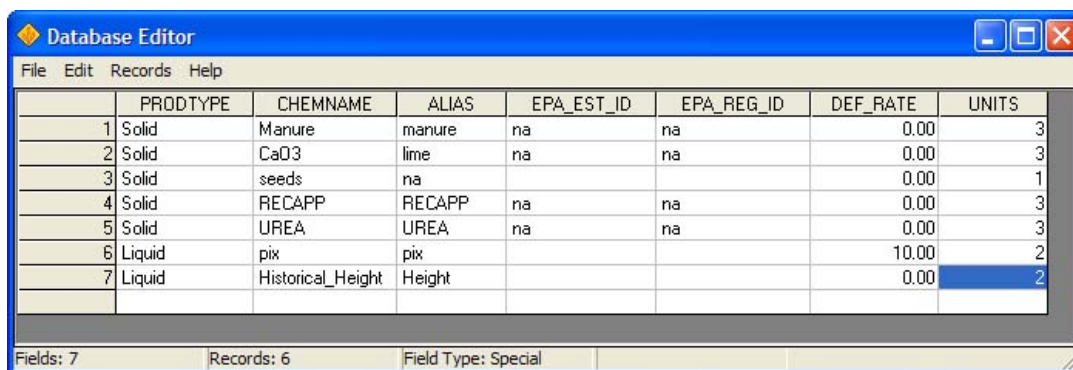
Product Name : Historical_Height

Historical_Height	Height
pix	pix

< Back Next > Cancel Help

FigureA13: Treatment Product Info Dialog

- a) Open the “product” database. Click Tools -> Processing Databases -> EPA... This will launch a Database Editor dialog shown in Figure A5.



Database Editor

File Edit Records Help

	PRODTYPE	CHEMNAME	ALIAS	EPA_EST_ID	EPA_REG_ID	DEF_RATE	UNITS
1	Solid	Manure	manure	na	na	0.00	3
2	Solid	CaO3	lime	na	na	0.00	3
3	Solid	seeds	na			0.00	1
4	Solid	RECAPP	RECAPP	na	na	0.00	3
5	Solid	UREA	UREA	na	na	0.00	3
6	Liquid	pix	pix			10.00	2
7	Liquid	Historical_Height	Height			0.00	2

Fields: 7 Records: 6 Field Type: Special

Figure A14: Database Editor Dialog

- b) Add a new product. Click Records -> Add. This will launch a new product dialog.
- c) Define a new product. Even though plant height does not conform to either solid or liquid, chose one or the other in the PRODTYPE field (it must be one or the other in order for the software to work). Enter a name

and alias in the CHEMNAME and ALIAS fields respectively. Enter a default rate in the DEF_RATE field. This should be something like 0.0 or 99.99 that can be easily identified in a data set in the event data is missing. There is no selection for units of height in the UNITS field so select anything here (oz/ac used in this research). The other parameters are not required so leave them blank. A completed new product dialog is shown in Figure A6.

Field	Value
PRODTYPE	Liquid
CHEMNAME	Historical_Height
ALIAS	Height
EPA_EST_ID	
EPA_REG_ID	
DEF_RATE	0.00
UNITS	oz/ac

Buttons: OK, Cancel, Delete

Figure A15: New Product Dialog

- d) Save and Exit. Click File -> Save and File -> Exit to leave the dialog.
- 2) Enter treatment equation. Highlight the desired product (the one created for plant height) and click Next. This will launch the Equation Editor dialog shown in Figure A7. Complete the dialog as shown in Figure A7. Select the “Image Layer” that corresponds to the IDW surface of plant height. Click Rate= and Apply Variable. Add a “;” at the end of the line. Without the “;” the equation will not work.
- 3) Complete the treatment map. Click Next in the Equation Editor. Be sure that “Process equations” is selected in the ensuing dialog and click Next. If prompted to save the equation, enter a name and click OK. This will launch a Process Treatment Equations dialog. Highlight the saved equation and click Finish. A Select Treatment Image File dialog will appear. Select a “Field” and “Layer” and de-select “Test” and click OK. The new treatment will be added to the map. To display, click the box next to the layer and click Apply to update the display.

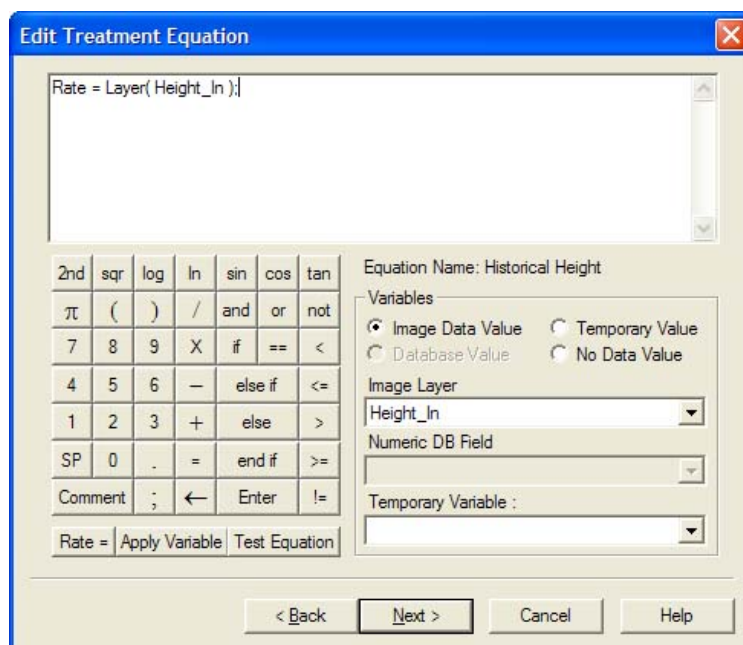


Figure A16: Equation Editor Dialog

- 4) Export VAF file. Right click on the treatment in the Table of Contents and select Files... De-select all except the “Treatment” corresponding to plant height. If more than one layer is desired in the prescription map, treatments must be merged together using Analysis -> Merge treatments; for historical plant height only one treatment is desired. Click Tools -> Export Image... -> VAF. Enter a name for the VAF file and click OK.

USING POCKET SPREADER

The newly created VAF file must be transferred onto the iPAQ before *Pocket Spreader* can begin transmitting historical plant height data to *HMAP*. This can be accomplished using Microsoft *ActiveSync*. The VAF file should be stored in a \My Documents\Pocket_Spreader directory on the iPAQ. This directory is also used by *Pocket Spreader* to store “as applied” data files. These files have the same name as the corresponding VAF file with a “_Channel1” at the end and must be deleted periodically to conserve memory on the iPAQ.

Pocket Spreader has a very simple interface and a limited number of user changeable parameters. The “GPS Options...” and “Controller Options...” should be configured for the corresponding devices. In the setup used in this research, GPS is connected to COM1 at 4800 baud and the VCD is connected to COM6 at 9600 baud. When the system is properly configured a VAF file can be loaded by clicking File -> Open and selecting the appropriate file. After the desired VAF file is open and the prescription map is visible on the screen, connect to the GPS by clicking File -> Connect. If the received GPS data is valid, a red dot will appear on the map and blink at

the current location. To begin transmitting data to *HMAP*, click File -> Start. This will also trigger *Pocket Spreader* to begin recording data. When finished measuring rate of growth with *HMAP*, stop the data transmission and recording by clicking File -> Stop. Click File -> Connect to disconnect from the GPS and File -> Exit to leave the program.

APPENDIX B

IDENTIFYING AVERAGE HEIGHT REGIONS IN PLANT HEIGHT DATA USING ARCGIS

IDENTIFYING AVERAGE HEIGHT REGIONS IN PLANT HEIGHT DATA USING ARCGIS

INTRODUCTION

Two basic steps are required to identify consistently average height regions in *HMAP* plant height data. First, points from each height data set within 1/8 standard deviation of the field average must be identified as average height locations. Second, points from consecutive dates within 40 feet of average height locations from all other dates must be identified. A variety of methods in GIS can be used to accomplish this task. Two methods were discussed briefly in previous articles of this thesis. The method using standard ESRI *ArcGIS* functions requires the least data manipulation and was the used for all data analysis in this research. This method is described in detail in this article.

IDENTIFYING AVERAGE HEIGHT LOCATIONS

A basic statistical analysis of plant height values is required to identify the field average (mean) and standard deviation. This analysis can be conducted prior to loading height data into *ArcGIS* or within *ArcGIS*. It is assumed that identifying these basic statistical parameters is simplistic; thus, such methods will not be discussed in this article. Average height locations can be identified using the following procedure:

- 1) Add “XY” data to *ArcGIS* and export a shape file. Click Tools -> Add XY data. Select the desired CSV text file and identify the fields in the dataset that correspond to the X and Y coordinates. Click OK and the “Event” data will be added to the map. Export the “Event” data into a shape file by right clicking on the newly added “Event” in the Table of Contents and selecting Data -> Export Data. In the ensuing dialog, select “Same as data layer” for Coordinate System and click OK when prompted to add a new layer to the map. Repeat this process for each plant height data set.
- 2) Select points within 1/8 standard deviation of the mean. Click Selection -> Select by Attributes. This will launch the select by attributes dialog. Develop an equation that describes points within 1/8 standard deviation of the mean. The selected “Layer” should correspond to the desired plant height data set. The equation should reference the field in the dataset corresponding plant height. A sample equation and is shown in Figure A8. Click Apply and OK. This will highlight all points in the dataset that conform to the equation. Export the selected data points into a new shape file by right clicking on the plant height data shape file in the Table of Contents and selecting Data -> Export Data. In the ensuing dialog, make sure that “Selected Features” is selected, click OK, and

click OK when prompted to add a new layer to the map. Repeat this process for each plant height data set.

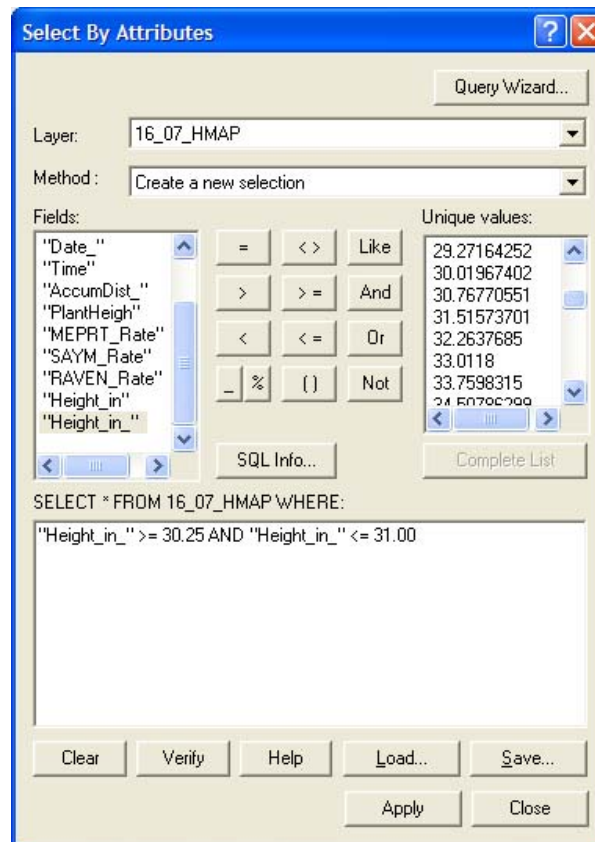


Figure A17: Sample Average Height Location Equation

IDENTIFYING AVERAGE HEIGHT REGIONS

An average height region is defined in this research as a circular region 40 feet in diameter that contains at least one average height location from every date plant height data was collected. The GIS may identify several locations in the field that conform to this criterion; however, it was shown that only two average height sampling regions are needed to characterize the general condition of the field. If more than two average height regions are identified, any two sites can equally characterize the field; therefore the most accessible sites can be selected from the identified sites. Average height regions can be identified using the following procedure:

- 1) Identify average height locations from the first date within 40 feet of average height locations from all other dates. Click Selection -> Select by Location. This will launch the Select by Location dialog. In the "I want to" field select "select features from". In the "the following layers" field select the average

height location shape file from the first date. In the “that” field select “are within a distance of”. In the “the features of this layer” field select the average height location shape file from the second date. In the “of” field enter 40.0 and select “feet”. A completed dialog is shown in Figure A9. Click Apply and the average height locations that meet the criterion will be highlighted. Do not click Close until completing step 2.

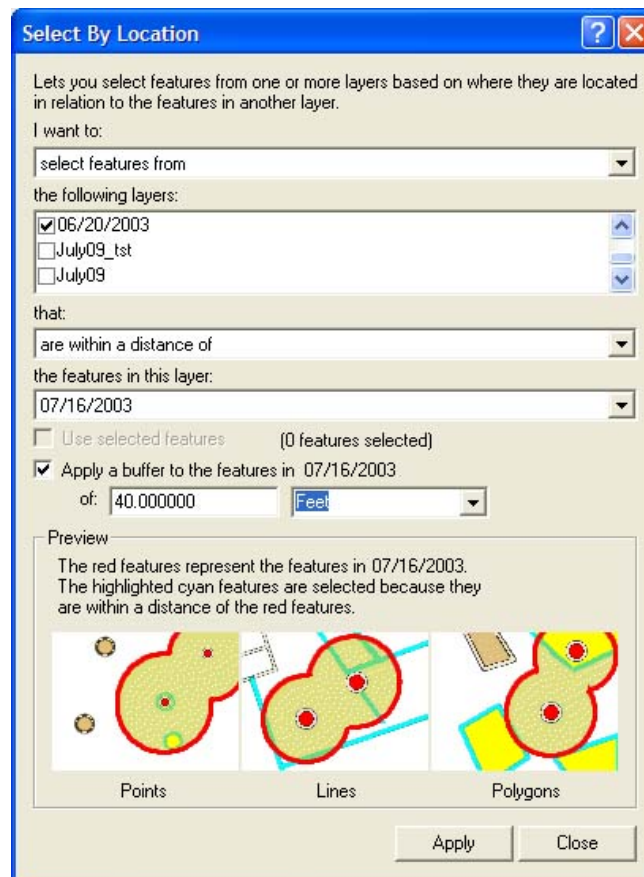


Figure A18: Completed Select by Location Dialog

- 2) Repeat the Select by Location procedure for all remaining dates after the second date. With the Select by Location dialog still open from step 1, change “I want to” from “select features from” to “select from the currently selected features in” and change “the features in this layer” to the average height location shape file from the next date. Click Apply and repeat this procedure for all dates. When finished, click Close to return to the map.
- 3) Create a new shape file to identify the center of each average height region. Right click on the average height location shape file from the first date and select Data -> Export Data. In the ensuing dialog, make sure that “Selected Features”

is selected, click OK, and click OK when prompted to add a new layer to the map.

- 4) Create average height regions. This step is necessary only to graphically display average height regions on the map. This can be accomplished using the Buffer Wizard. Click Tools -> Buffer Wizard. In the ensuing dialog, select the shape file that contains the center of each average height region. Click Next. Select "At a specified distance" and enter 40 feet. Click Next and select No for "Dissolve barriers between". Click Finish and the average height regions will be displayed on the map.

VITA

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| 1979 | Born March 27 in Bryan, Texas. |
| 1997 | Graduated from Ames High School, Ames, Iowa. |
| 1997-99 | Studied Mechanical Engineering at The University of Iowa, Iowa City, Iowa. |
| 1998-02 | Participated in coop program with John Deere, Ottumwa, Iowa. |
| 2002 | B.S. with distinction, Agricultural Engineering, Iowa State University, Ames, Iowa. |
| 2002-04 | Graduate Assistant, Department of Biological and Agricultural Engineering, Texas A&M University, College Station, Texas. |
| 2004 | M.S., Biological and Agricultural Engineering, Texas A&M University, College Station, Texas. |
| 2004 | Returned to John Deere Ottumwa Works as a full time engineer. |